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CLEAN ACCESS, MEASUREMENT, AND SAMPLING OF ELLSWORTH SUBGLACIAL LAKE: A METHOD FOR EXPLORING DEEP ANTARCTIC SUBGLACIAL LAKE ENVIRONMENTS

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[1] Antarctic subglacial lakes are thought to be extreme habitats for microbial life and may contain important records of ice sheet history and climate change within their lake floor sediments. To find whether or not this is true, and to answer the science questions that would follow, direct measurement and sampling of these environments are required. Ever since the water depth of Vostok Subglacial Lake was shown to be >500 m, attention has been given to how these unique, ancient, and pristine environments may be entered without contamination and adverse disturbance. Several organizations have offered guidelines on the desirable cleanliness and sterility requirements for direct sampling experiments, including the U.S. National Academy of Sciences and the Scientific Committee on Antarctic Research. Here we summarize the scientific protocols and methods being developed for the exploration of Ellsworth Subglacial Lake in West Antarctica, planned for 2012–2013, which we offer as a guide to future subglacial environment research missions. The proposed exploration involves accessing the lake using a hot-water drill and deploying a sampling probe and sediment corer to allow sample collection. We focus here on how this can be undertaken with minimal environmental impact while maximizing scientific return without compromising the environment for future experiments.

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1. INTRODUCTION

[2] Antarctic *subglacial lakes* are large pools of water located at the ice sheet base (lakes in excess of 500 m in length were listed in the inventories of *Siegert et al.* [1996, 2005]). (Italicized terms are defined in the glossary, after the main text.) They exist because *geothermal heating* even at a background level of ~40–70 mW m^{-2} [*Siegert and Dowdeswell*, 1996] is sufficient to raise the temperature at the bottom of thick (3–4 km) ice to the pressure melting point, despite the severely cold conditions at the ice surface. The water that forms flows under gravity and ice pressure and collects in topographic hollows. The size and depth of a subglacial lake depend largely on the basal *geomorphology*. Where the bed is flat, lakes are generally thought to be small and shallow. Where water fills whole valleys or fault-bounded basins, however, subglacial lakes can acquire huge dimensions. *Vostok Subglacial Lake*, the best known and largest subglacial lake, commonly referred to as Lake Vostok, occupies a trough beneath ~4 km of ice and is over 250 km in length and in excess of 500 m deep [*Kapitsa et al.*, 1996; *Siegert et al.*, 2011].

[3] It is hypothesized that Antarctic subglacial lakes house unique forms of microbial life adapted to these extreme habitats [*Ellis-Evans and Wynn-Williams*, 1996]. An additional hypothesis is that in some settings, subglacial lake bed sediments accumulate records of past environmental change

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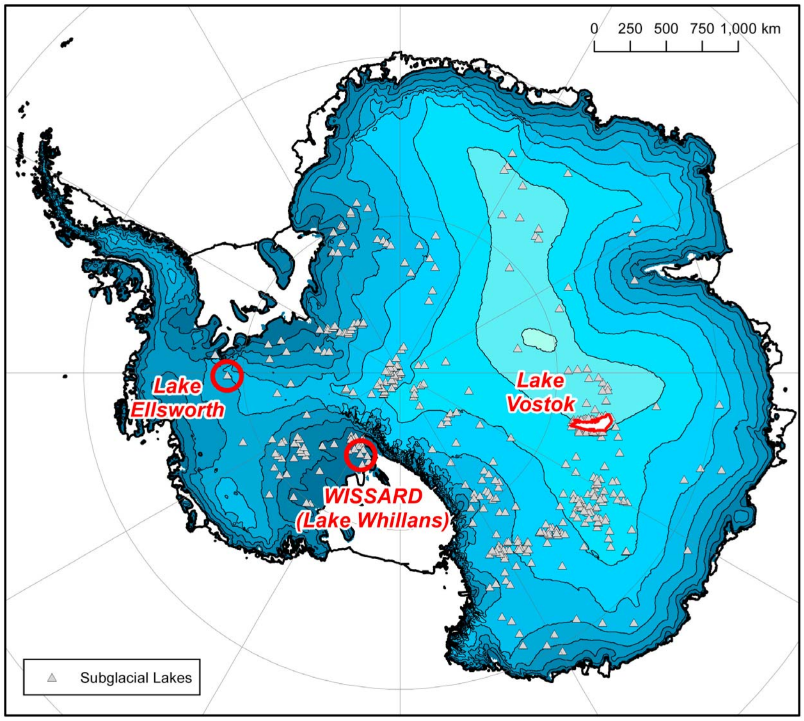


Figure 1. The location of 386 Antarctic subglacial lakes [from *Wright and Siegert*, 2011]. Lake Ellsworth, Lake Vostok, and Lake Whillans (the site of the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) program) are annotated.

that may provide critical insights into the glacial history of Antarctica [*Barrett*, 1999]. Testing these hypotheses requires in situ exploration and sampling.

[4] More than 350 subglacial lakes are known to exist in Antarctica [*Wright and Siegert*, 2011] (Figure 1). One lake in West Antarctica, officially named Ellsworth Subglacial Lake (hereinafter called Lake Ellsworth), has been shown to be an excellent candidate for exploration [*Siegert et al.*, 2004]. The lake, first identified in a reconnaissance survey in the late 1970s [*Drewry and Meldrum*, 1978], lies beneath >3 km of ice and is 14.7 km long, 3 km wide, and, at its deepest, ~160 m deep [*Woodward et al.*, 2010]. Undertaking direct measurement and sampling of the lake will allow the two hypotheses, which are the fundamental drivers of subglacial lake research, to be tested by (1) determining the presence, origin, evolution, and maintenance of life in an Antarctic subglacial lake through direct measurement, sampling, and analysis and (2) revealing the paleoenvironment and glacial history of (in this case) the West Antarctic Ice Sheet (WAIS), by recovering a sedimentary record from the lake floor.

[5] Lake Ellsworth has the potential to host microorganisms that have been isolated from the rest of the biosphere for several hundred thousand years, sufficient time for development of novel *phylogenies* and *physiologies*. If this is the case, and can be proven, the results will advance knowledge on how life functions in these dark and likely ultraoligotrophic systems, analogous to other Antarctic subglacial aquatic environments, the Earth's oceans during periods of total global ice cover (e.g., the *snowball Earth hypothesis* [*Hoffman et al.*, 1998]), and *Europa*, the Jovian moon that has a liquid ocean beneath a crust of ice. Such findings will be of direct relevance to knowledge on the development, limitations on, and evolution of life on Earth and elsewhere in the solar system.

[6] Sediments from the floor of Lake Ellsworth will help to evaluate WAIS history and therefore present-day stability. The history of the WAIS is poorly known yet is critical to assessing the present-day risk of ice sheet collapse and consequent sea level rise. In particular, the date when the ice sheet last decayed, and therefore the conditions that lead to ice sheet disintegration, are currently unknown. *Ice cores* cannot provide this information because they are restricted to the age of the ice itself, which in West Antarctica is likely to be ~100,000 years (e.g., depth-age data of *Blunier et al.* [1998]). *Diatoms* in subglacial mud suggest central West Antarctica was ice-free less than 600,000 years ago [*Scherer et al.*, 1998], whereas sedimentary records from a distal site beside the *Transantarctic Mountains*, *ANDRILL* AND-1B, suggest the last time central West Antarctica was ice-free was around 1 million years ago [*Naish et al.*, 2009]. A good location to provide more precise constraints is a sedimentary environment located on the interior flank of the *Bentley Subglacial Trench* [see *Lythe and Vaughan*, 2001]. According to the model of *DeConto et al.* [2007], this is the area of the central WAIS most susceptible to early ice sheet decay. The floor of Lake Ellsworth is consequently well suited to contain a record of the WAIS since its last formation, because the lake water protects the sediments from any basal erosion by ice. The sediment will also

likely contain a record of changes in the lake environment through time.

[7] Addressing the two hypotheses by direct measurement and sampling must be undertaken in a clean manner with minimal environmental impact, adding confidence to the scientific results and minimizing the long-term impact on the lake. The proposed exploration will access the lake using a *hot-water drill* and deploy first a *probe*, and then a *sediment corer*, to measure physical and chemical parameters in situ and collect water and sediment samples. The drilling and sampling exercise will take an estimated 4 days, within a several-month-long program of construction and removal of lake access equipment. The program must build, test, and deploy all the equipment necessary to complete the experiment, to ensure appropriate standards are maintained. The deployment of heavy equipment, which is a considerable obstacle to working in remote regions, has been shown to be possible at the Lake Ellsworth location, based on several deep-field reconnaissance studies.

[8] Previous geophysical investigative work was undertaken at Lake Ellsworth during the 2007–2008 and 2008–2009 seasons to characterize the lake, aid the design of the access program, and provide baseline data for environmental considerations. This included *radio echo sounding* (RES) surveys to establish the thickness and basal characteristics of the ice; *seismic surveys* of lake *bathymetry*, water body thickness, and underlying sediments; *GPS* measurements of the ice flow above the lake; and collection of shallow ice cores to calculate ice accumulation rates and perform a preliminary analysis of microbiology and geochemistry in the overlying ice [*Woodward et al.*, 2010; *Ross et al.*, 2011a].

[9] The methods and protocols established by the Lake Ellsworth program demonstrate, generically, how subglacial lake exploration can be undertaken in a way that maximizes scientific return without affecting the environment. They have been developed after considering advice on subglacial lake exploration by the *U.S. National Academy of Sciences* report on environmental stewardship of subglacial lake exploration [*U.S. National Research Council*, 2007] (NAS-EASAE) and the *Scientific Committee on Antarctic Research* (SCAR) code of conduct on subglacial aquatic environments [*Alekhina et al.*, 2011].

[10] Although several papers review the occurrence and physical characteristics of subglacial lakes [e.g., *Dowdeswell and Siegert*, 1999; *Siegert*, 2005], descriptions of the background data, equipment, instrumentation, and techniques needed for subglacial lake exploration have yet to be published. This paper reviews the baseline geophysical data and technological developments necessary for clean access of, and scientific exploration within, Lake Ellsworth. We first present geophysical data to characterize the physical environment of the lake. Second, the method of lake access via hot-water drilling is outlined. Third, we discuss the likely level of gases (most likely air) within Lake Ellsworth and examine the consequences for expulsion of gas to the ice surface once lake access is achieved (and look at program risks). Fourth, we describe the instruments designed to take direct measurements and samples of the lake and the cleanliness controls that are in place. Fifth, we briefly indicate the laboratory experiments that will be made on samples, which are needed to address the project's hypotheses. The paper represents a blueprint for other subglacial access missions in Antarctica and, in future years, for extra terrestrial ice-covered water bodies.

[11] Two other projects aim to access subglacial lakes in the next few years; a Russian-led mission to Lake Vostok in central East Antarctica and a U.S. program on Lake Whillans in the Siple Coast of West Antarctica (Figure 1). While all three programs aim to access the subglacial environment, there are some distinctions that may make it less easy for the techniques developed in these other programs to be applied elsewhere. For the case of the Lake Vostok experiment, lake access is possible as a consequence of an existing deep borehole [*Lukin and Bulat*, 2011]. The plan is to further deepen the borehole via coring to the surface of the lake. Ice coring is highly time consuming and requires substantial infrastructure, making its use as a subglacial access technique difficult to apply generally. Ice coring also requires the use of an antifreeze fluid, and while such liquid does not prohibit clean access to the bed it certainly makes it more challenging than a borehole filled with water. Hence, we do not feel the Lake Vostok experiment can be copied easily in experiments on other subglacial lakes. The U.S. program to Lake Whillans, on the other hand, is similar to Lake Ellsworth in that it will use hot-water drilling [*Fricker et al.*, 2011]. However, the ice thickness over this lake is ~800 m, and the lake itself is only a few meters deep. Thus, while the experiment is certainly interesting scientifically, the application of the techniques to other deep subglacial lakes is not immediately transferable. We acknowledge that there may be alternative ways in which the program's hypotheses may be tested, and while we are confident that those chosen for this investigation are optimal, they may not necessarily work as well in other situations (see Appendix A).

2. BASELINE CONDITIONS OF LAKE ELLSWORTH

2.1. Geophysical Surveys of Lake Ellsworth

[12] Prior to access, direct measurement, and sampling of subglacial lakes, definition of their physical characteristics and topographic setting is necessary. Geophysical methods such as RES and seismic reflection are ideal for making these observations and for providing data to constrain numerical modeling of the physical processes (e.g., melting, refreezing, water circulation) operating within subglacial lakes. These data and models can then be used to guide the selection of access locations and sampling and measurement strategies.

[13] Since Lake Ellsworth was chosen as a suitable target for access and study [*Siegert et al.*, 2004], several ground and airborne geophysical survey campaigns have been undertaken [*Vaughan et al.*, 2007; *Woodward et al.*, 2010; *Ross et al.*, 2011a] with the aim of defining the geometry and physical characteristics of the lake. Here we review and highlight our current understanding of the lake and its surrounding environment with emphasis on those findings that have particular relevance to the lake access experiment.

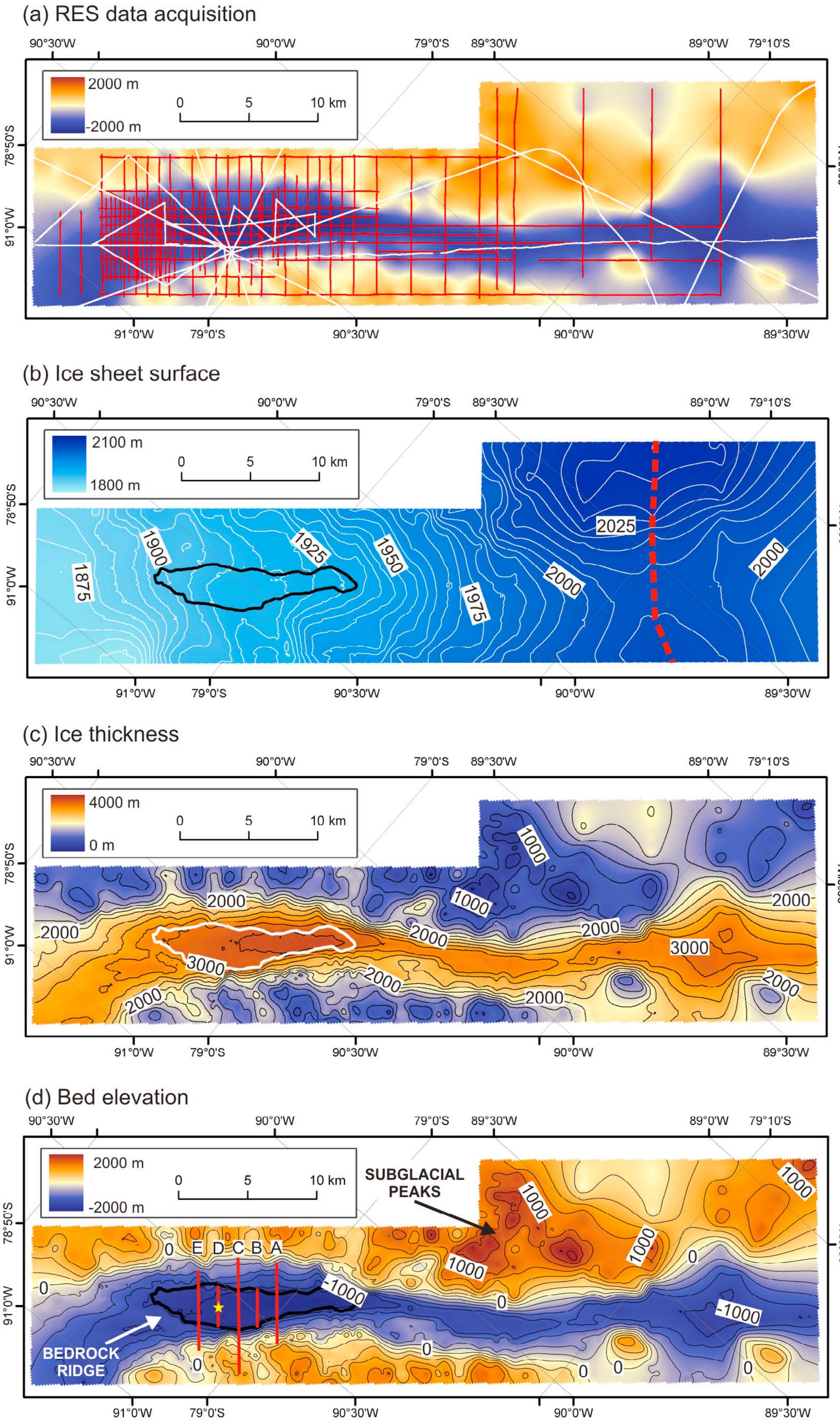

(a) RES data acquisition
2000 m
-2000 m
0 5 10 km
(b) Ice sheet surface
2100 m
1800 m
1875
1900
1925
1950
1975
2000
2025
(c) Ice thickness
4000 m
0 m
1000
2000
3000
(d) Bed elevation
2000 m
-2000 m
SUBGLACIAL PEAKS
E D C B A
BEDROCK RIDGE
1000
0
-1000
90°30'W
90°0'W
79°0'S
89°30'W
89°0'W
79°10'S
78°50'S
91°0'W
89°0'W
90°30'W
90°0'W
89°30'W

Figure 2

2.1.1. Morphology of the Subglacial Catchment

[14] Lake Ellsworth is one of a series of subglacial lakes located in deep, SE-NW trending, subglacial valleys within the Ellsworth Subglacial Highlands [*Vaughan et al.*, 2007]. The Lake Ellsworth trough is a deep (1500 to >2500 m), steep-sided subglacial trough, constrained by high, rugged subglacial topography. Geomorphological evidence (e.g., U-shaped form of the trough, hanging valleys, valley over-deepenings, bedrock ridges) indicates that trough formation predates the current ice sheet (N. Ross et al., manuscript in preparation, 2012). The trough was most likely incised by an outlet glacier flowing from an ice cap centered over the present Ellsworth Subglacial Highlands, perhaps in a fjord-like setting when the present-day Bentley Subglacial Trench was a marine embayment [*Vaughan et al.*, 2007; N. Ross et al., manuscript in preparation, 2012].

[15] The upper reaches of Lake Ellsworth trough are relatively narrow (2.5–3.5 km across) and shallow (800–950 m below sea level), but the trough broadens (5.5–6.5 km across) and deepens (>1000 m below sea level) in the vicinity of the lake (Figure 2). The lake itself is located in a significant over-deepening, a feature characteristic of formerly glaciated valleys in mountainous environments. The down-ice limit of this over-deepening is marked by a prominent bedrock ridge that crosses the entire width of the trough at an oblique angle, impounding the lake (Figure 2). This 6 km long ridge is a major landform, with a ridge crest ~200 m above the elevation of the adjoining lake surface, and is likely to play a key role in controlling the nature and timing of drainage from the lake (see section 2.3).

[16] The morphology of the subglacial trough has had an important role in determining the location of Lake Ellsworth. The accumulation of water at the base of an ice sheet to form subglacial lakes is dependent on the interplay between the topographic setting (i.e., the basal geomorphology) and the overburden pressure of the overlying ice sheet. While in other settings small changes in the configuration of the ice sheet surface may divert water along alternative flow paths [*Pattyn*, 2008; *Wright et al.*, 2008], the topographic setting of the Lake Ellsworth system would appear to be particularly favorable for subglacial lake development and maintenance [*Woodward et al.*, 2010].

[17] Unless substantial ice sheet reconfiguration were to occur (e.g., significant migration of the nearby ice divide, or glacial- to interglacial-scale changes in ice sheet thickness), it is unlikely that Lake Ellsworth would succumb to the sudden or persistent drainage events [e.g., *Wingham et al.*, 2006; *Smith et al.*, 2009] characteristic of subglacial lakes in areas of more subdued topography [*Dowdeswell and Siegert*, 2003]. This would suggest that Lake Ellsworth is a relatively stable, long-lived feature of the West Antarctic subglacial environment [*Ross et al.*, 2011b].

2.1.2. Geometry of the Water Body

[18] Seismic data can provide key information on subglacial lake geometry, and the physical properties and thickness of sublake sedimentary packages [*Filina et al.*, 2008; *Peters et al.*, 2008; *Woodward et al.*, 2010]. Such information cannot be acquired from RES surveys because electromagnetic energy is considerably attenuated at *ice-water interfaces* and cannot penetrate any great distance into subglacial water bodies [*Gorman and Siegert*, 1999]. However, by integrating the data acquired using these two complementary geophysical methods, our understanding of subglacial aquatic environments can be greatly enhanced.

[19] Numerous and closely spaced RES and seismic survey lines have allowed the ice-water interface of Lake Ellsworth to be mapped in unprecedented detail. The lake is 14.7 km long, with a total area (in plan view) of ~28.9 km^2 (Figure 3), and exists beneath 3280–2930 m of ice. Narrow (generally <1.5 km) in its upper third, the lake broadens further down-ice (up to 3.05 km), before narrowing into a small embayment in its lowermost 2.5 km (Figure 3). "Sagging" of the ice sheet as it flows over the up-ice grounding line, and "buckling" of the ice sheet at the down-ice grounding line, were observed in the single airborne RES line flown over Lake Ellsworth in the 1970s, with an ice-water interface concave at the up-ice end of the lake and convex at the down-ice end [*Siegert et al.*, 2004].

[20] The ice-water interface is clearly characterized by a steep up-ice dip, the result of the ice sheet surface slope above the lake (Figure 3) (if the overlying ice is freely floating, subglacial lakes will have a slope that is ~–11 times the slope of the overlying ice sheet surface). The data show that the lake has a marked surface gradient: ~330 m over the ~11 km from its deepest point (1361 m below ellipsoid) to its shallowest point (1030 m below ellipsoid). This is a very steep lake surface gradient along the direction of ice flow in comparison to some larger subglacial lakes (e.g., Lake Vostok, where the lake ice gradient is ~400 m over 250 km) but is not unique among other lakes [*Siegert et al.*, 2005; *Wright and Siegert*, 2011]. The gradient of the ice-water interface is likely to result in differential melting and freezing across the lake, which would in turn drive or enhance water circulation within the water body [*Siegert et al.*, 2001; *Woodward et al.*, 2010] (see section 2.2). Although this prominent, up-ice dipping slope is the dominant feature of the ice-water interface, a number of local

Figure 2. Maps produced from Deep Look Radio Echo Sounder (DELORES) radio echo sounding (RES) and other geophysical data sets. (a) Location of acquired RES data. Red lines represent DELORES data; white lines represent British Antarctic Survey (BAS) and Centro de Estudios Científicos (CECS) 150 MHz data also used for the gridding of ice thickness and subglacial bed grids. (b) GPS-derived ice sheet surface topography. Contours are at intervals of 5 m. Red-dashed line shows approximate position of ice divide. Black polygon is the outline of Lake Ellsworth. (c) Ice thickness grid, with contours at intervals of 200 m. (d) Subglacial topography, with contours at intervals of 200 m. Seismic lines are labeled A–E. The parts of the seismic lines colored red show the extent of the acquired seismic data. The proposed lake access location is shown with a yellow star. All images have a common scale. Ice flow is roughly right to left in all images.

characteristics have specific implications for the access experiment.

[21] The shape of the ice-water interface suggests that the lake is not freely floating across its full extent. Preliminary hydrological analysis indicates it may only be the central body of the lake (where the hydraulic head is constant) that is floating freely (N. Ross et al., manuscript in preparation, 2012). Along the lateral margins of the lake, the ice-water

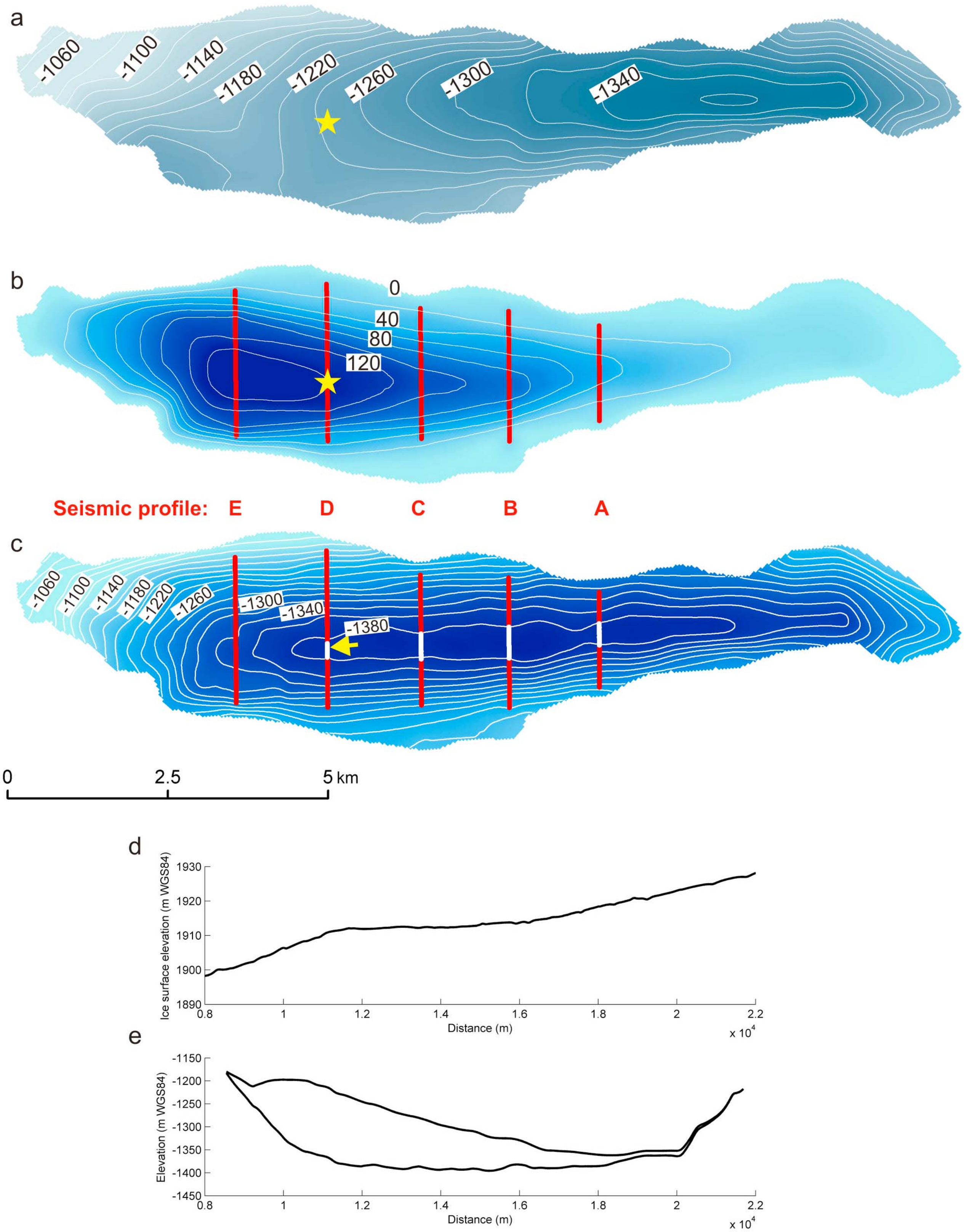


Figure 3

interface slopes downward toward the lakes central axis (Figure 3). This morphology is believed to be a consequence of the high *bridging stresses* generated by the steep bedrock sidewalls of the trough, which prevent the ice sheet from floating completely.

[22] Where the ice sheet first flows over the upstream end of the lake, the slope of the ice sheet bed for a distance of ~1.7 km is opposite to the general slope of the ice-water interface and is remarkably steep (Figure 3). The reversal of slope direction may be due to the overlying ice not being fully afloat over this section of the lake, either because of bridging stresses, the abrupt shift from "grounded" to "floating" ice [*Weertman*, 1974], the geomorphology of the trough, or because the ice is flowing over water-saturated sediments (i.e., a "swampy" subglacial aquatic environment) rather than over a pure water body [e.g., *Siegert and Ridley*, 1998]. Evidence in support of basal sediments is provided by the "fuzzy" nature of the RES bed reflections over this part of the ice-water interface, suggesting either water-saturated material or sediment-rich basal ice. Such a scenario is consistent with schematic models of subglacial lake depositional systems [*Bentley et al.*, 2011] (see section 2.1.3).

[23] In the down-ice parts of the lake there are two features of note. First, the ice-water interface steepens markedly in the lowermost third of the lake, both toward the grounding line at the bottom end of the lake (although it maintains its up-ice dip) and toward the right-lateral margin (Figure 3). Second, the northwest corner of the lake is characterized by a localized but very prominent decline in elevation toward the down-ice grounding line of the lake (Figure 3). The steepening of the ice-water interface in the lowermost third of the lake is caused by a corresponding increase in the ice sheet surface slope. This most likely reflects a combination of bridging stresses and basal conditions farther down-ice where the ice grounds on the prominent bedrock ridge that impounds the lake. To counteract the resistance to flow generated by enhanced basal shear stress over the ridge, the ice surface slope upstream of the landform will increase, in turn maintaining a steep ice-water interface over the lake. The localized northwest corner of the lake is well sampled, by both RES and seismic data (Figure 2), and corresponds to the pronounced localized area of high basal refreezing (>8 cm yr^{-1}) in the water circulation model of *Woodward et al.* [2010]. However, the ice-water interface used in the modeling experiment is inferior to the one presented here (i.e., it was an "early" product that did not include RES data from the 2008–2009 field season). The pronounced area of basal refreezing in the model may therefore be the result of shortcomings in the input data used, rather than representing a physically realistic result. However, it does highlight the influence that the morphology of this part of the ice-water interface has on controlling the physical interactions between the lake and the overlying ice.

[24] The seismic reflection data acquired at Lake Ellsworth have revealed the depth and bathymetry of the lake [*Woodward et al.*, 2010]. On the basis of these measurements, the estimated volume of Lake Ellsworth is 1.37 km^3 ± 0.2 km [*Woodward et al.*, 2010]. The results from the seismic surveys underpin the lake access experiment and have been used to model circulation in the water body (see section 2.2).

[25] Both the maximum and mean lake depth, as measured on each of the five seismic reflection survey lines, increase down lake (from SE to NW) [*Woodward et al.*, 2010], with a maximum measured depth for the lake of 156 m. The seismograms show that the lake is positioned in the base of the over-deepened *U-shaped trough*. The seismic data also reveal some smaller-scale geomorphology of interest. Four seismic lines show evidence of benches or terraces on the lake floor. The gridded data (Figure 3) clearly demonstrate the U-shaped morphology of the lake bed. The grids also show the nearly constant elevation (below ellipsoid) of the lake floor along the lakes long axis (i.e., the area within the −1380 m contour between lines A and D) (Figure 3). Between seismic lines D and E, however, it is apparent that the floor of the lake begins to slope upward. Although there is no constraint from seismic data down-ice of line E, based on line E and the RES survey lines that delimit the outline of the lake, and hence the elevation of the regrounding line, it is clear that this upward slope must continue, and increase in incline, toward the bedrock ridge identified down-ice of the lake. Between the lowermost measured depth on seismic line E and the uppermost crest of the bedrock ridge, there is an almost 1 in 4 gradient. Prominent over-deepenings with abrupt terminations such as these are "classic" landforms of glaciated valley systems or fjords [*Sugden and John*, 1976].

[26] The geophysical data from Lake Ellsworth show that the point of maximum water depth in subglacial lakes does not necessarily correspond to the point of lowermost elevation; the greatest water column thickness (156 m) was measured near the center of seismic line E, but the lowest point of the lake floor is on seismic line B, at 1393 m below ellipsoid. In fact, lines A–D all have significant areas of lake floor 1380 m below ellipsoid, despite all having maximum measured water column thicknesses of <143 m. In contrast,

Figure 3. Gridded seismic data sets: (a) ice-water interface (integrated seismic and RES data), (b) water column thickness (seismic data only), and (c) lake bed topography (ice-water interface minus water column thickness). Yellow stars and arrows indicate the proposed access location. (d) Ice surface elevation over the lake. (e) Elevation of the ice sheet base and lake floor. Contours for Figures 3a, 3b, and 3c are at 20 m intervals. The red lines in Figures 3b and 3c represent the measured positions of the lake bed (and water column thickness). The parts highlighted white in Figure 3c represent the areas of the lake bed below −1380 m. Ice flow throughout the diagram is from right to left. All elevation measurements are in meters relative to the WGS84 ellipsoid. For the seismic data, static GPS measurements were made at shot points (every 240 m); surface elevations for each seismic trace (every 10 m) were from linear interpolation between shot points. For the RES data, ice surface elevations were established for each trace using kinematic GPS measurements acquired at 1 Hz.

the lowest measured elevation on line E, which has the thickest water column, is 1354 m below ellipsoid.

2.1.3. Sedimentary Environment: Evidence and Depositional Models

[27] Analysis of the seismic reflection data indicates the lake bed is composed of high-porosity, low-density sediments. These sediments have acoustic properties very similar to material found on the deep-ocean floor, indicative of deposition in a low-energy environment [*Smith et al.*, 2008]. Analysis suggests that this sedimentary sequence is a minimum of 2 m thick and that there is no evidence for consolidation of these sediments by overriding ice [*Smith et al.*, 2008].

[28] *Bentley et al.* [2011] presented a two-dimensional (2-D) conceptual model of the possible sedimentary system within Lake Ellsworth. Understanding the sedimentary system is important because it has significant implications for determining the utility of the sediments as archives of ice sheet evolution, past environmental changes, and the presence of life within the lake. *Bentley et al.* [2011] suggested that Lake Ellsworth would be subject to sediment input from (1) rain-out from the overlying ice, (2) the melt of debris-rich basal ice, (3) subglacial meltwaters, and (4) chemical sedimentation. Although each of these processes will deliver sediment into Lake Ellsworth, the dominant process is likely to be input from sediment-rich basal meltwaters sourced from the base of the U-shaped trough, up-ice of the lake [*Bentley et al.*, 2011]. As these meltwaters enter the lake, deposition from sediment-rich meltwaters and debris-rich basal ice may lead to the development of landforms akin to grounding-line fans or morainal banks [*Bentley et al.*, 2011]. However, as the meltwater flows through the lake system (probably as an underflow along the lake floor) and deposition becomes increasingly distal from the sediment input point, the sediment being deposited will become increasingly finer and will be characterized by reducing rates of deposition [*Bentley et al.*, 2011]. Geophysical data have shown that the parts of Lake Ellsworth likely to be characterized by distal sedimentation also correspond to the deepest regions where the water column is greatest [*Woodward et al.*, 2010]. The down-ice sector of the lake therefore includes the best locations for the recovery of a sedimentary archive of ice sheet history and life in the lake. This sector is less likely to have been adversely affected by erosion by grounded ice or episodic lake drainage and will be characterized by persistent low sedimentation rates [*Woodward et al.*, 2010; *Bentley et al.*, 2011]. Because underflows are likely to be the dominant process determining sediment transport, and therefore deposition, in the lake, it is thought that the parts of Lake Ellsworth more distal from the up-ice influx point will be characterized by planar laminated silt and clay deposits, with an absence of coarser sediments that can cause practical challenges for sediment recovery [*Bentley et al.*, 2011]. However, a more complex sedimentary sequence (e.g., with interfingering deposits) may be found in Lake Ellsworth if material is delivered by gravity-driven slumping of sediments from the slopes of the lake bed.

2.2. Physical Processes in the Lake

[29] *Woodward et al.* [2010] and *Thoma et al.* [2010] observed that Lake Ellsworth may have a particularly unusual thermodynamic configuration. Because of its geometry and the range of elevation of its water body, a critical pressure (P_c) boundary known as the *line of maximum density* (LOMD) may pass through the lake. Above the LOMD, where overburden pressure is "low" relative to the P_c, water warmed by the geothermal heat flux and the release of latent heat during freezing is dense and will sink. However, below the LOMD, where overburden pressure is "high" relative to the P_c, any heated water will rise through buoyancy [*Thoma et al.*, 2010]. Although this has theoretical implications for water circulation within Lake Ellsworth, the model results of *Woodward et al.* [2010] showed that the steeply sloping ice-water interface is the dominant driver of water circulation within the lake, and circulation will occur throughout the lake irrespective of the position of the LOMD in the lake.

[30] The hydrological balance of the lake is likely to be affected heavily by whether the system is open or closed. In an open system, meltwater into the lake can be balanced by outflow. In a closed system, however, water cannot escape and so the hydrological balance must be maintained by the formation of accretion ice, as has been found at Lake Vostok [*Jouzel et al.*, 1999]. Modeling is able to inform us of the likely water circulation and accretion rates under a closed system (described below) but is currently unable to offer insights into the processes in an open system. For example, the input of sediment-rich underflows in an open system would have a significant impact on modeled circulation patterns within the lake, but this process is not able to be modeled simply without more information than is currently to hand.

[31] *Woodward et al.* [2010] used the 3-D numerical fluid-dynamics model, ROMBAX [*Thoma et al.*, 2007], to assess (1) likely water circulation patterns in Lake Ellsworth and (2) interactions between the lake and the overlying ice sheet (i.e., whether the ice-water interface is melting, freezing, or refreezing). Although such a model is unlikely to be entirely applicable for Lake Ellsworth (because it assumes a closed system), it nevertheless provides insights into the processes that may drive circulation within the lake. The model suggests that approximately half the lake area (the up-ice half) is characterized by basal melt while the other half (the down-ice half) is dominated by basal refreezing, leading to the formation of accretion ice. Mean calculated melt rates are 3.8 ± 0.7 cm yr^{-1}, compared to the value of ~17 cm yr^{-1} suggested by *Siegert et al.* [2004], while freeze-on leads to a mean accretion ice thickness of 12.5 ± 3.5 m. While geophysical and borehole evidence for accretion ice has been presented for other subglacial lakes [e.g., *Bell et al.*, 2002], so far no unequivocal evidence for the presence of accretion ice has been observed in the

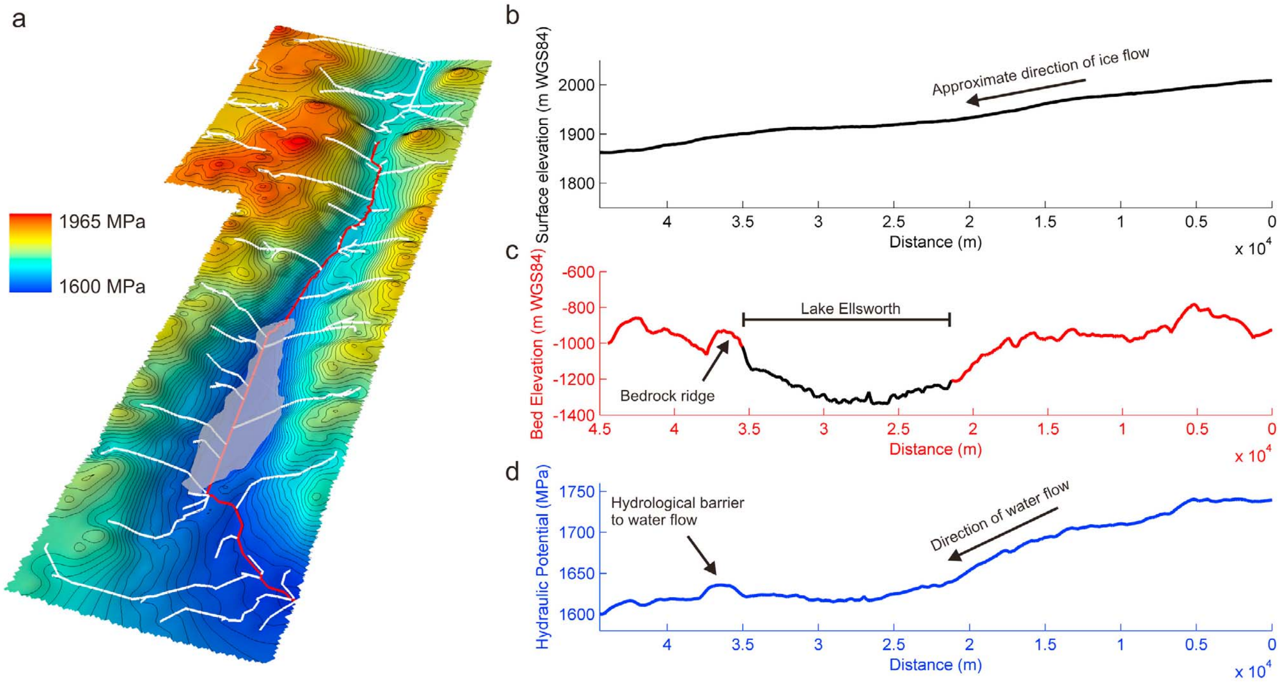


Figure 4. (a) Three-dimensional representation of the hydrological potential of the Lake Ellsworth catchment. Basal water will flow from areas of high (red) to low (blue) pressure, perpendicular to the contours. Lake Ellsworth is clearly a hydrological sink for the entire upstream basal hydrological catchment. Also shown (as a red line) is the location of a profile (roughly along the axis of the catchment hydrological low) used to establish the hydrological profile in Figures 3b–3d. (b) Ice surface elevation. (c) Bed elevation. (d) Hydraulic potential along the hydrological profile. In Figure 4c the black line defines the extent of Lake Ellsworth.

radargrams from Lake Ellsworth. A zone of "fuzzy" basal reflections (in comparison to RES basal reflections over the central parts of the lake) has been identified in the parts of the lake close to the down-ice grounding line of the lake. However, in addition to reflecting the presence of accretion ice, this could equally, and perhaps more probably, be interpreted as evidence for a basal environment characterized by sediment-rich ice or water-saturated sediments. In addition, the seismic data show no systematic difference in reflection strengths between the seismic lines, which would be likely if *frazil ice* formation, a precursor to accretion ice formation, were taking place [*Woodward et al.*, 2010]. However, it should be noted that the formation of congelation ice would not necessarily result in expected variations in reflection strength [*Woodward et al.*, 2010].

2.3. Lake Hydrological Balance: An Open or a Closed System?

[32] Because of the implications that it has for evaluating the potential risks associated with blowout (i.e., the release of lake-held air gases to the ice surface; see section 4) on lake access, it is important to assess whether a subglacial lake has an open or closed hydrological system. Two methods of analysis derived from RES data can be used to infer the hydrological system: (1) analysis of the *hydrological potential* and (2) analysis of the radar energy (power) returned from the sub-ice interface.

[33] A map of the hydrological potential (Figure 4), used to predict the direction in which water will flow at the base of the ice (assuming it is characterized entirely by basal melting), shows that basal water flow in the Ellsworth Subglacial Lake catchment is strongly influenced by the bedrock topography. Basal meltwaters from the upper hydrological catchment can potentially flow along the base of the subglacial bedrock trough for a distance of ~20 km from the hydrological divide to the lake (Figure 4). This shows that basal meltwaters from the upstream catchment will flow, apparently unimpeded, into Lake Ellsworth. Some limited ponding of water may occur upstream of the lake; however; two of the RES survey lines across ice flow in the upper hydrological catchment are characterized by sections with bright basal returns, suggesting localized pooling (one feature with a diameter of <1 km).

[34] Downstream of the lake the situation is rather different. The hydrological potential data clearly show that the prominent bedrock ridge that impounds the bottom end of Lake Ellsworth is an obstacle to outflow of lake water. This increases the risk of the lake having a "closed" hydrological system.

[35] To investigate the probability of an open or closed system, a map of the reflected electromagnetic energy returned from the boundary between the ice and underlying materials (*bed-reflection power* (BRP)) around Lake Ellsworth has been produced (Figure 5). It is widely accepted

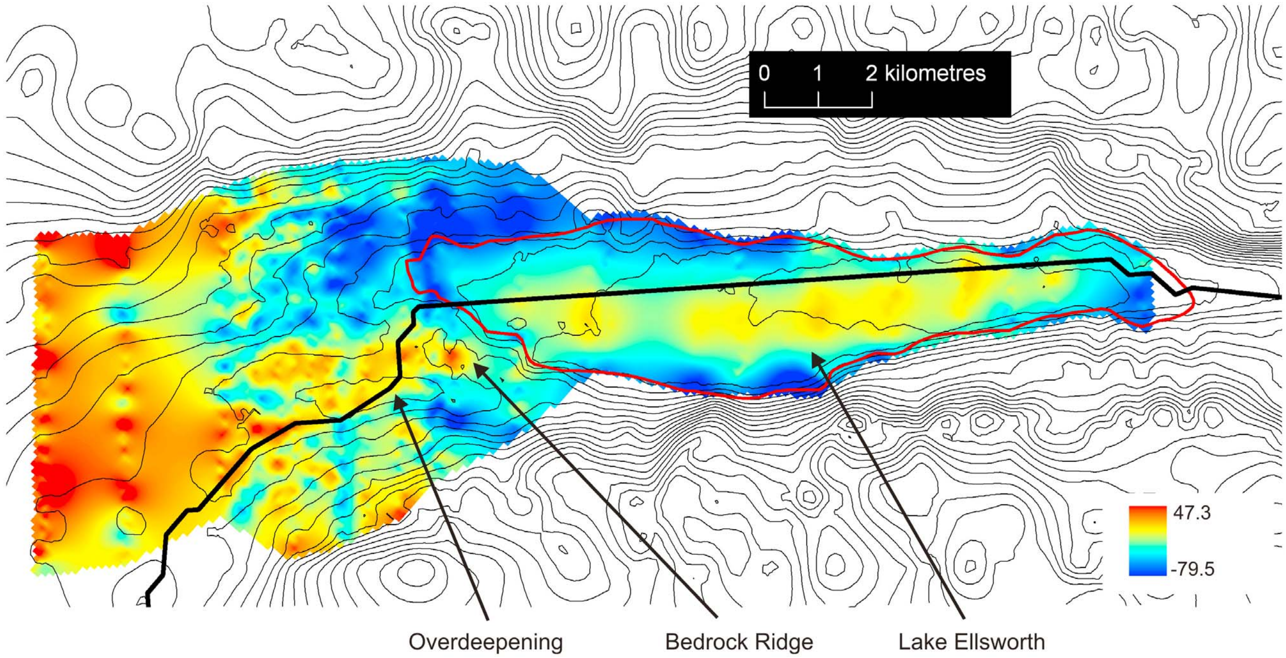


Figure 5. Map of bed-reflection power (BRP) over and downstream of Lake Ellsworth. The scale is arbitrary, but red represents higher values of BRP and blue colors represent lower values of BRP. Black lines are elevation contours at 100 m intervals. The bold black line defines the position of the profile data from Figure 4. Key features are also labeled. The zone of higher BRP at the left in the image likely reflects a combination of a thinner ice column and possibly the presence of more widespread basal water.

that high-amplitude returns from the base of ice sheets in RES data represent water bodies or water-saturated sediments. By mapping the spatial distribution of BRP, we use this established relationship to assess whether water is able to exit the lake by outflow between the ice and the bedrock ridge.

[36] A zone of BRP elevated relative to surrounding values extends from the bedrock ridge downstream (Figure 5). The onset of the enhanced BRP zone corresponds with a low in the topography and hydrological potential in the elongated ridge. The simplest explanation for the elevated BRP values mapped downstream of Lake Ellsworth is that they represent a narrow zone of basal water. We suggest that this is caused by outflow from Lake Ellsworth and that consequently the lake is characterized as an open hydrological system to some degree.

[37] It should be noted that our analysis of BRP must be considered preliminary, as the calculations have not been corrected for attenuation of radar energy in the ice column caused by englacial temperatures and chemistry. Instead, the values presented are simply the "raw" measurements of power returned from the bed of the ice. Despite the preliminary nature of the BRP analysis, we have some confidence in the current interpretations for the following two reasons: (1) The spatial pattern of the zone of elevated BRP (relative to the surrounding ice sheet bed) appears to be independent of topography (the top of the elongate ridge is associated with relatively low values of BRP, while an overdeepening just downstream of the ridge is associated with elevated values (Figure 5), the opposite of what one would expect if the pattern were due to ice thickness), suggesting that the elevated BRP is likely due to factors other than variations in ice thickness; and (2) the clear correspondence between the spatial pattern of high BRP and the topographic and hydrological low in the bedrock ridge would be expected if water was outflowing (to some degree) from the lake.

2.4. Ice Cores and Lake Biogeochemistry

[38] Shallow ice cores retrieved from the ice sheet surface above Lake Ellsworth [*Ross et al.*, 2011a] have been analyzed for biogeochemistry. Using these analyses we calculate the likely hydrochemistry of the lake assuming a closed system. By doing this, we reveal the likely maximum lake geochemistry (i.e., maximum likely chemical concentrations). In a perfectly open system, the water chemistry will resemble that of the ice, providing end-member scenarios.

[39] Previous work by *Siegert et al.* [2007] estimated that the residence time of water was ~5000 years if the lake was *hydrologically closed* and that there had been ~80 renewals of lake water in the past 400,000 years (i.e., since marine isotope stage 11). This suggested that the chemical composition of the lake water might be up to 80 times more concentrated that of the incoming ice melt if there were no other sources or sinks of ions within the lake, because only ~0.1% of solute from meltwater is incorporated into accretion ice during freezing [e.g., *Jouzel et al.*, 1999]. The calculations were based on the lake dimensions assumed from the one RES line that was available at that time. However, the revised dimensions of the lake reported here, when coupled with average melt and accretion rates of 4 cm yr^{-1},

TABLE 1. Estimates of the Maximum Chemical Composition of Water in Lake Ellsworth Making the Simple Assumption That the Lake Is a Closed System and That All Solute From Melting Meteoric Ice Accumulates in the Lake[a]

	H^+	pH	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-
Average Byrd ice core	1.8	5.7	~1.0	0.4	1.5	0.05	0.13	2.0	1.0	0.7	~1.2
Provisional surface firn and ice concentrations	NA	NA	8.9	0.65	2.8	0.57	NA	5.3	1.4	0.83	~8.2
Inferred Lake Ellsworth (from Byrd core)	300	>3.52	170	68	250	8.5	<22	340	170	<120	~200
Inferred Lake Ellsworth (from provisional surface data)	NA	NA	1500	110	470	96	NA	900	240	<140	~1400

[a]Units are μeq/L. NA indicates not measured so no data are available.

suggest that the maximum residence time of water in a closed lake is ~2370 years, suggesting also that there might have been as many as 170 water renewals over the past 400,000 years. This in turn suggests that the maximum chemical composition of the lake water (if the lake was closed hydrologically) is up to 170 times that of the incoming ice melt providing there were no other sources or sinks of ions within the lake.

[40] *Siegert et al.* [2007] assumed that the chemistry of meteoric ice melt is equivalent to that of the mean chemistry recorded in the *Byrd ice core*, giving the expected chemistry of lake water in Table 1. Provisional geochemical data for the mean composition of firn and ice in the top 20 m of the recently acquired surface ice cores from above Lake Ellsworth are also given in Table 1. These surface ice core values are higher in most species, which may be a consequence of rock dust blown from the Ellsworth Mountains and factors such as proximity to sources of sea salt aerosol and the relative amounts of sublimation of snow prior to deposition. The consequence of these higher concentrations is that the lake waters may be more solute rich than first estimated, assuming closed conditions, with overall solute concentrations being comparable with the more concentrated basal meltwaters sampled to date from beneath smaller warm- and *polythermal-based glaciers* in the Northern Hemisphere [*Skidmore*, 2011]. The inferred concentrations of Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, and HCO_3^- that we estimate are probably conservative, because these ions are generated from interactions between glacial flour from bedrock erosion and ice melt and so may be generated within the lake, or in hydrological flow paths en route to the lake. The inferred concentrations of H^+, NH_4^+, and NO_3^- are probably too high, since glacial flour uses up H^+ in chemical weathering actions, and microbial activity will remove NH_4^+ and NO_3^-. Microbial activity may also change levels of SO_4^{2-} and HCO_3^-. We estimate that the pH of the lake water will be ~6 (Table 1 notes it is >3.52 in a purely closed system) and that NO_3^- and NH_4^+ concentrations will be around 1 μeq L^{-1}, similar to those estimated in Lake Vostok [*Siegert et al.*, 2003].

2.5. Location of the Lake Access Hole

[41] On the basis of the geophysical data, the lake access site (as illustrated in Figures 2 and 3) is chosen where (1) the lake is deepest (although the water column, at 143 m ± 1.5 m, is less thick than that downstream on seismic line E, owing to the inclined ice roof), which means a full water column record will be recovered; (2) the floor of the lake is flat, meaning that lake floor sediments are less likely to be affected by slope depositional and transport processes; (3) it is distal from the dominant source of sediment input (the upstream end of the lake), thereby maximizing the probability of a short sediment core providing a long-term record of ice sheet history; (4) modeling and radar data suggest the ice-water interface is unaffected by the buildup of accretion ice, which is advantageous for lake access via hot-water drilling; (5) the overlying ice is (relatively) thin at 3155 ± 10 m; and (6) seismic evidence suggests a sediment thickness of at least 2 m below the lake floor.

3. HOT-WATER DRILL

[42] Hot-water drilling is the most effective means of obtaining rapid, clean access to Lake Ellsworth (see Appendix A for discussion on alternative approaches). The technique has been used successfully by several institutions, including the British Antarctic Survey (BAS), for more than 20 years to access the water beneath ice shelves, with present drilling having penetrated over 2000 m of ice on both Rutford Ice Stream (*RABID* program) and at South Pole (*IceCube* program). Readily available industrial equipment has been used to build the bespoke drilling system for accessing Lake Ellsworth. While it is designed specifically for the Lake Ellsworth project, it will offer clean access to other subglacial environments in future years.

[43] The drilling concept is simple, as shown in Figure 6. Water is filtered, UV treated, and then heated via a heat exchanger and pumped, at high pressure, through the drill hose to a nozzle that jets hot water to melt the ice. The hose and nozzle are lowered slowly to form a very straight hole, as gravity is used as the steering mechanism. The water from the nozzle uses the melted hole as the return conduit.

[44] A submersible borehole pump installed near the surface, but below the lake's hydrological level (~284 m below the ice surface, calculated from the ice density profile and the assumption that the ice column is floating), returns water to a number of large surface storage tanks, which are maintained at several degrees above freezing. The water is then reused by the hot-water drill. Three generators provide electrical power for the drill. By using (and recycling) melted glacier ice as the drilling fluid, the hole created by the drill will meet the project's cleanliness criteria, minimizing the potential for contamination of the lake by the drilling fluid.

[45] During drilling, the water flow, pressure, and temperature will remain fixed (3 L s^{-1}, 2000 psi, 90°C), while

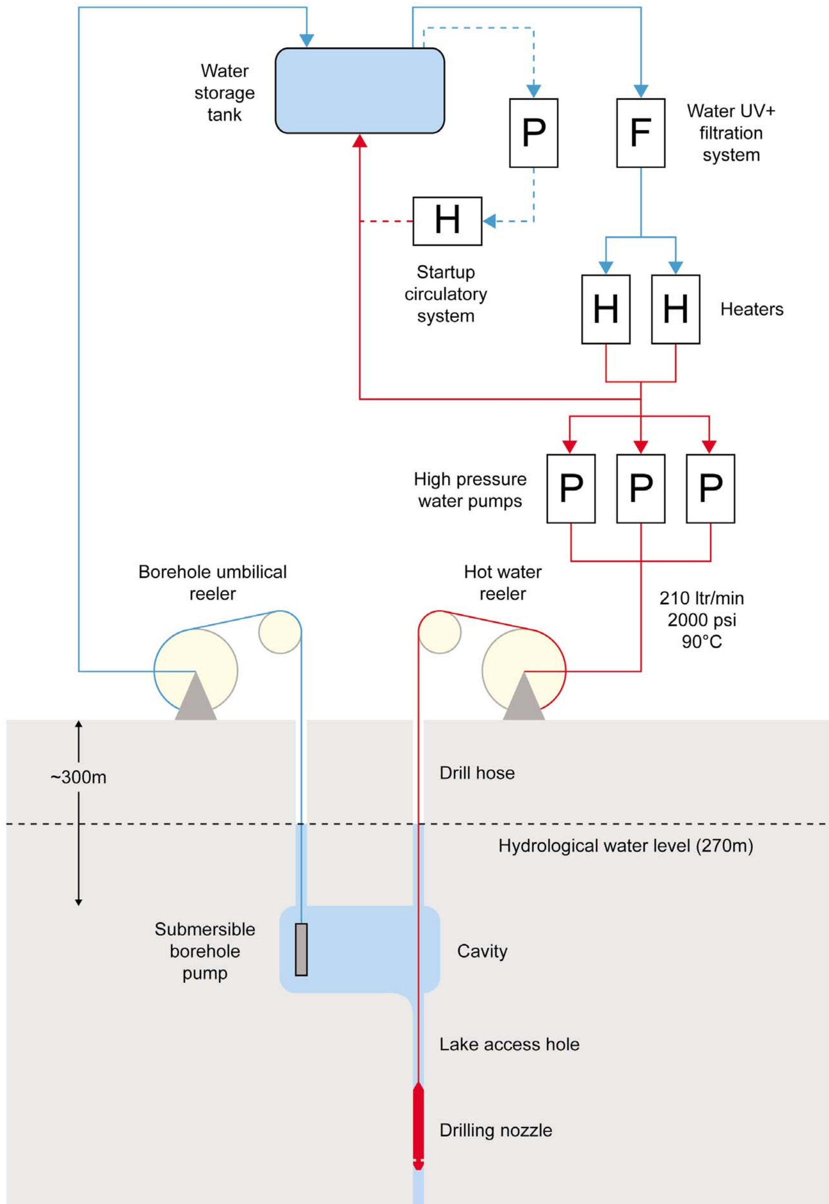


Figure 6. Schematic diagram of the hot-water drill system. H, heaters; P, pumps; F, filters.

the drilling speed is varied between 1.0 and 0.5 m min^{-1} to create a hole that will have a uniform diameter of 36 cm at the end of the drilling process. Creating the lake access hole into the lake will take around 3 days. Before reaching the lake, the water level in the hole will be drawn down a few meters below the hydrological lake level to prevent drill water from entering the lake.

[46] A filtration system will be used to treat drill water to remove suspended solid particles, including bacteria and viruses. The water will pass through a five-stage filtration system utilizing spun bonded, pleated, and membrane filter elements with absolute micron ratings of 20, 5, 1, 0.45, and 0.2, before being UV treated (using 254 nm wavelength, at a power of 200 W, to kill anything that passes the filter). This water will then be heated and pumped down a single 3.4 km length of hose to a drill nozzle. During the initial stages of drilling, the hose on the winch reel and the drill nozzle will be subjected to temperatures of up to 90°C for at least 15 h. During the entire drilling process, the smooth-bore plastic-lined drill hose will be continually flushed for at least 3 days by over 800 t of hot filtered water, thus internally rinsing the hose and nozzle. The outer surface of the hose will be scrubbed using high-pressure water jets and then passed through a UV collar just prior to the hose entering the hole. Once in the hole, the hose exterior is bathed in the admixture of filtered drill water and meltwater that flows up the hole at a rate of 1.8 m per minute to be reused by the drill, thus flushing any microorganisms released from the ice to the surface for filtration. Samples of drill fluid will be analyzed to assess the quality of microbial control and to provide reference data for lake samples.

[47] At each stage of the filtration and UV system, tapping points will allow water samples to be collected and analyzed. The final filter stage will be passed through a 0.2 μm filter. All filters will be provided with dual redundancy in order to allow new filters to be brought online without any interruption to the water flow. Differential pressure across the filters will be monitored. Increases in these differential pressures will indicate the health of the individual filters. At a set differential pressure the filters will be changed out for new filters. All filters will be available for postoperational analyses, critical for determination of microbial load in the drill fluid.

[48] Detecting when the drill reaches the lake will be achieved using pressure sensors close to the submersible pumps; these will monitor the water level adjustment when the hydraulic connection between the hole and the lake is made. Once the hole has been enlarged (by controlling the drill's rate of descent) at the ice–lake water interface, the drill is recovered and the hole is available for water and sediment sampling. Closure of the hole, because of refreezing, reduces the diameter at a rate of ~0.6 cm h^{-1}, resulting in ~24 h when the hole will remain large enough to deploy and recover equipment. If additional lake access time is required, the hole can be reamed for as long as fuel remains available.

[49] Recent hot-water drilling on Rutford Ice Stream demonstrated the following weaknesses in an earlier hot-water deep drilling system: drill hose coupling failure; periodic cessation of drilling to add lengths of drilling hose; and exposure to weather changes as a consequence of operating in open conditions. To eliminate the first two issues, a single 3.4 km length of thermoplastic hose with double Kevlar braids is used to meet the pressure requirements together with a single long pitch Vectran fiber outer braid strength member. To reduce the impact of weather conditions, the drill system will be housed in a covered shipping container. During July and August 2011, the entire system was tested to resolve technical issues, provide valuable training for the engineers and scientists who will operate the drill at the field site, and ensure contamination controls can be demonstrated.

4. LIKELIHOOD OF GAS (AIR) HYDRATES AND SURFACE BLOWOUT ON LAKE ACCESS

[50] The level of gas (air) concentration within Antarctic subglacial lakes will vary according to local glaciological conditions and the duration over which these conditions have occurred. If open conditions have not prevailed, under a closed hydrological situation where lake water is created by melting ice and is lost only by accretion, dissolved gas concentrations must increase (as the accretion ice contains very little, if any, gas compared with the overriding meteoric ice). If completely closed, and if conditions persist for long periods (up to many millennia), the dissolved gas concentration may reach saturation, at which time gas *clathrates* will accumulate [*McKay et al.*, 2003]. This presents potentially serious issues for lake access experiments because gas blowout at the surface, no matter how unlikely, requires mitigation and planning.

[51] We outline here the various ways in which gas may enter a deep-ice borehole penetrating a subglacial lake, and, with specific reference to Lake Ellsworth, we estimate the period of hydrological closure necessary for gas clathrate development. Gas blowout cannot occur unless Lake Ellsworth contains at least ~30% by volume of clathrate material, which would take at least 100,000 years to develop. The likelihood of this situation occurring is very low. Potential (engineering) mitigation measures can be designed to avoid gas blowout, but we conclude that they are not necessary given the very low risk of gas blowout occurrence. However, we recommend the temperature of the drill fluid be reduced prior to lake penetration to further reduce the risk of blowout and that site staff are, as a precautionary measure, moved from a predefined exclusion zone on lake access. Regardless of the likelihood, even if negligible, the potential for a blowout needs assessment and mitigation, as the safety consequences are potentially serious. This issue has been recognized by SCAR, whose code of conduct for the exploration and research of subglacial aquatic environments [*Alekhina et al.*, 2011] states that "Water pressures and partial pressures of gases in lakes should be estimated prior to drilling in order to avoid down-flow contamination or destabilization of gas hydrates, respectively. Preparatory steps should also be taken for potential blowout situations."

[52] We also analyze the likelihood of a worst-case scenario of clathrate accumulation in the lake and what the implications would be if lake water were allowed to enter the access borehole. A blowout emanating from a subglacial lake can conceivably be in three ways, namely, water pressure derived, dissolved gas derived, and clathrate derived. Finally, we discuss ways in which a blowout can be mitigated.

4.1. Water Pressure–Derived Blowout

[53] For water to surge up the borehole and fountain over the surface during the drilling to the bed, the hydrological head of the basal waters must be above the level of the ice surface. In practice, this usually means that high water pressures are generated via subglacial hydraulic connections to a source at an elevation well above the level of the ice at which penetration occurs. These conditions cannot occur in the vicinity of Subglacial Lake Ellsworth or indeed any subglacial lake at or near the ice divide, as the ice surface is commonly several hundred meters above the bed level and the head of water pressure between the lake and the nearby divide is small.

[54] RES measurements of basal topography around Lake Ellsworth show that water generation is likely to come from elevations that are only 500 m higher than the edge of the lake (Figure 2). The ice sheet is known to "float" on the central region of the lake (i.e., the basal slope is ~−11 times the surface slope) and is therefore in hydrological equilibrium with the lake water [*Siegert et al.*, 2004; *Vaughan et al.*, 2007].

[55] As ice is less dense than water, the pressure at the base of a borehole completely filled with water will be higher than the ice sheet basal pressure and therefore the basal water pressure. As a consequence, a borehole water level equivalent to the ice thickness multiplied by the fraction of the densities of ice over water needs to be established prior to lake access, to allow the borehole and ice sheet/lake pressures to be approximately equal. If this is not done, borehole water is likely to flow into the lake. For the Lake Ellsworth drill site, approximately 284 m of water will need to be pumped out of the borehole and maintained at that level during the access experiment. If the borehole is underpressured with respect to the lake, however, lake water will escape up the borehole to the level at which the pressure will equilibrate (following some small-scale oscillation). This is a normal feature of ice sheet bed access [*Bentley and Koci*, 2007].

[56] We believe there is a zero risk of blowout upon access to Subglacial Lake Ellsworth due to lake water pressure alone. This conclusion may not hold for subglacial lakes far away from the ice divide, however. A *digital elevation model* (DEM) and a simple hydrological calculation will assist in planning for this access issue for lakes in such regions, such as Lake Whillans in the Siple Coast (Figure 1).

4.2. Gas Pressure Derived From Melting Meteoric Ice

[57] We calculate the likely maximum gas concentration released by hot-water drilling by assuming that the overlying meteoric ice at Ellsworth has the same gas content as the meteoric ice overlying Lake Vostok. The average composition of Vostok meteoric ice contains 0.09 cm^3 g^{-1} of gas at *STP* (standard temperature and pressure, 25°C, and 1 atms respectively), equivalent to 0.09 L kg^{-1} or ~90 L m^{-3} of ice [*Lipenkov and Istomin*, 2001]. The bulk of this is nitrogen (~79%) and oxygen (~21%). We assume that Ellsworth meteoric ice contains this gas content and composition too, and it follows that Lake Ellsworth contains at least this amount of gas with a comparable composition.

[58] It is important to realize that *dissolved gases* form bubbles and degas safely during normal hot-water drilling of meteoric ice. This is because the atmospheric gas content of meteoric ice exceeds the solubility of these gases in the resultant ice melt, as the following illustration shows. We assume that the water used for drilling contains air saturated at the surface at a temperature close to 0°C, as is realistic for meltwaters in the holding tank. This is a maximum value since gas solubility decreases with temperature. This gas content is ~0.03 cm^3 g^{-1} (~0.04 cm^3 g^{-1} × 80% (the approximate air pressure of the Ellsworth drilling site in relation to sea level)). Melted meteoric ice will equilibrate to this value as it returns to the surface and is held in the holding tanks for ~2.5 h. The amount of degassing can be calculated as follows. Some 0.09–0.03 or ~0.06 cm^3 of gas must diffuse out of the holding tank for each gram of meteoric ice that is drilled.

[59] To determine the drilling melt rate, we assume that the drill nozzle water flow rate is fixed at 180 kg min^{-1}, the temperature near the surface is 90°C, falling to 47°C at the base of the ice, while the ice temperature is −32°C in the upper 2000 m of the ice column, increasing to the freezing point at the base. This gives a melting rate of 171 kg min^{-1} near the surface (180 kg min^{-1} × 4.2 kJ kg^{-1} °C^{-1} × 90°C/ 333 kJ kg^{-1} + (2 kJ kg^{-1} °C^{-1} × 32°C)) and 107 kg min^{-1} at the ice base (180 kg min^{-1} × 4.2 kJ kg^{-1} °C^{-1} × 47°C/ 333 kJ kg^{-1} + (2 kJ $kg^{-1\circ}$ C^{-1} × 0°C)). Therefore, during the routine drilling of meteoric ice, the typical gas venting rate is initially ~10 L min^{-1} of gas (171 kg min^{-1} × 0.06 L kg^{-1}), reducing to ~6.5 L min^{-1} of gas (107 kg min^{-1} × 0.06 L kg^{-1}) at the bottom of the hole. The air pressure at the Ellsworth drilling site is ~0.8 atms and the air temperature is ~–15°C (or ~258 K), and so the gas volumes at the drilling site will be ~8% higher than at STP, since the effect of the temperature difference on gas volume, which serves to deflate the gas volume, is slightly less than the decrease in pressure, which serves to inflate the gas volume.

[60] Shallow drilling of boreholes on ice masses around the globe produces gas bubbles that rise harmlessly through the water column with no blowout problems. To date, deep drilling of meteoric ice (e.g., RABID and IceCube) has also encountered no gas or blowout problems since two further factors serve to hold the gas in solution until the deep drill fluid returns closer to the surface. First, the solubility of gases increases with depth. Crudely, the solubility of O_2 and N_2 increases to ~0.77 × 10^{-3} and 1.48 × 10^{-3} mole fractions, respectively, at ~28 MPa, the pressure in Lake Ellsworth [after *Lipenkov and Istomin*, 2001]. One mole of water weighs 18 g and 1 mol of gas occupies 22.4 L at STP. Oxygen solubility is calculated at 0.96 cm^3 g^{-1} (0.77/1000 (moles of O_2 per mole of H_2O) × 22.4 (liters of O_2 at STP per mole of O_2) × 1000 (cm^3 L^{-1}) × 1/18) and, similarly for nitrogen, solubility equals 1.84 cm^3 g^{-1} (1.48/1000 (mole/mole) × 22.4 L per mole × 1000 (cm^3 L^{-1}) × 1/18 (mole g^{-1})), making a total of ~2.8 cm^3 g^{-1}. So Lake Ellsworth water can hold ~2.8 cm^3 g^{-1} of gas (at STP).

[61] Meteoric ice melted at the surface can vent gas via diffusion through the water-atmosphere interface in the drilling water reservoir that the circulated drill fluid is returned into. Bubbles may form during shallow drilling, but they are insufficient to cause a blowout of dangerous proportions being so close to the surface. As drilling proceeds to greater depth, any gas or clathrate released from the meteoric ice is dissolved into solution because the gas solubility increases with depth (to a maximum of 2.8 cm^3 g^{-1} compared with 0.09 cm^3 g^{-1} in the melted meteoric ice).

[62] The second factor is that the mixing ratio of circulating drilling fluid (undersaturated with gas at <0.3 cm^3 g^{-1}) and melted meteoric ice is high, so that gas saturation is never actually approached. The circulating drill fluid will be warmer than 0°C and so holds less gas, but this general assertion is true given the water depths (up to 3000 m) that we are dealing with. Circulating drill fluid that reaches the surface will be slightly oversaturated but will vent gas via either the formation of bubbles near the surface or diffusion as it makes free contact with the atmosphere in the holding tanks, before being reheated and recirculated.

[63] In conclusion, there is no risk of blowout because the water is highly under-saturated (0.09 cm^3 g^{-1}) compared to the gas solubility at 28 MPa (~2.8 cm^3 g^{-1}).

4.3. Gas Pressure–Derived Blowout: Open Lake System

[64] In an open hydrological situation, gases may enter a subglacial lake via melting of gas-containing ice, such as meteoric ice, and are removed from the lake by water transport to downstream environments. Recent satellite investigations of ice surface elevation changes shows that many subglacial lakes fill and discharge significant (>1 km^3) volumes [*Smith et al.*, 2008], sometimes resulting in transport of basal water over large (>100 km) distances [*Wingham et al.*, 2006; *Carter et al.*, 2009]. This suggests that much of the Antarctic ice sheet base can be thought of as an open hydrological system.

[65] In a completely open hydrological system, the levels of gases in the lake water will be the same as in the meteoric ice; hence the calculations detailed above hold here. Any lake water which entered the base of the drill hole, say, to 20 m, would not make it back to the surface without mixing with existing drill fluid in the hole. Normal diffusional venting would remove this gas at the surface. This conclusion is likely to hold true for all *hydrologically open* subglacial aquatic environments and is supported by at least two boreholes drilled to the ice sheet base [*Bentley and Koci*, 2007]. In both the European Ice Coring in Antarctica (EPICA) Project at Dronning Maud Land (*EDML*) (East Antarctica) and the North Greenland Ice Core Project (*NGRIP*), neither experienced "blowouts." In the case of NGRIP, a subglacial aquatic environment was hit. The water from this environment entered the bottom meters of the hole and froze, forming pink ice. It was later found that the pink coloration was due to iron oxidation, meaning that the original waters were lacking in oxygen at the bed [*Christner et al.*, 2008].

4.4. Gas Pressure–Derived Blowout: Closed Lake System

[66] In this case, gases enter the lake due to melting of gas-enriched ice, but none is taken out of the lake due to there being no transport of lake water downstream. Water balance is maintained by creation and transport of accretion ice, which contains virtually no gas [*McKay et al.*, 2003]. Hence, gas buildup in the lake can occur.

[67] Accretion ice has been identified in both ice core and RES records for Lake Vostok and in RES records for *Lake Concordia*. Modeling confirms that all lakes will have accretion ice formation in a closed system, and hence there will be gas buildup. No accretion ice has been identified in RES records over Lake Ellsworth, however. The calculations below assume a permanently hydrologically closed system for Lake Ellsworth, the likelihood of which was discussed in section 2.3. *Woodward et al.* [2010] show that under a closed system, the average freezing/melt rates are 4 cm yr^{-1}, with a maximum value of 15 cm yr^{-1}. In the calculations below, we assume that meteoric ice melts into 50% of the ice roof at rates of both 15 and 4 cm yr^{-1}, and accretion ice freezes onto the other 50% of the roof at the same rates. We assume the meteoric ice melting into the lake has a gas content of 0.09 cm^3 g^{-1} and that all gas remains in the lake. We assume the lake volume to be 1.37 km^3 and the surface area to be 28.9 km^2. So the residence time of water in the lake (equivalent to how long it takes for melting/freezing to produce/remove the entire volume of water in the lake) is ~630 years (melt rate = 15 cm yr^{-1}) (1.37 km^3 × 10^9 m^3 km^{-3}/(28.9 km^2 × 0.5 × 10^6 m^2 km^{-2} × 0.15 m yr^{-1})) or 2370 years (melt rate = 4 cm yr^{-1}) (1.37 km^3 × 10^9 m^3 km^{-3}/(28.9 km^2 × 0.5 × 10^6 m^2 km^{-2} × 0.04 m yr^{-1})).

[68] For each residence time, the concentration of gas in the lake increases by 0.09 cm^3 g^{-1}. This continues until the lake water becomes saturated with gas at 2.8 cm^3 g^{-1}. The time required for waters to reach gas saturation is therefore approximately 19,600 years (melt rate = 15 cm yr yr^{-1}) (630 years × 2.8 cm^3 g^{-1}/0.09 cm^3 g^{-1}) or 73,700 years (melt rate = 4 cm yr^{-1}) (2370 years × 2.8 cm^3 g^{-1}/0.09 cm^3 g^{-1}). This calculation is approximate because nitrogen and oxygen saturate at slightly different times and assumes that normal box model rules apply, such as homogeneity in the box (or a completely mixed lake in our case). Thereafter, melting meteoric ice into a closed Lake Ellsworth causes clathrates to form. This becomes a potentially big problem for access because, for example, if the lake has existed since marine isotope stage 11 (400 ka), then the clathrate content in terms of gas at the surface could be as high as ~54 cm^3 g^{-1} (melt rate = 15 cm yr^{-1}) ((400,000 years × 0.09 cm^3 g^{-1}/630 years) – 2.8 cm^3 g^{-1}) or ~12 cm^3 g^{-1} (melt rate = 4 cm yr^{-1}) ((400,000 years × 0.09 cm^3 g^{-1}/2370 years) – 2.8 cm^3 g^{-1}). These are very large numbers and would imply (in the worst case) that all of the lake water is bound up in clathrate gas cages. Any free clathrates would either float if CO_2 was in low (<10%) concentration [*McKay et al.*, 2003], which is most likely, or else it would sink (and would probably not then be a problem for lake access).

[69] We can calculate how much of a problem this might be on lake access by assuming that this type of worst-case, clathrate-rich water enters the base of the borehole, which near to lake access will have an area of 0.1 m^2, to a height of 20 m. This means that 2 m^3 of lake water could enter the base of the borehole. If this was warmed by a few degrees C, due to mixing with drilling fluid, for example, the clathrate may destabilize to produce a gas bubble. This would produce a potential water displacement at STP of 1080 m ((2 m^3 × 54 cm^3 g^{-1} × 10^{-6} m^3 cm^{-3} × 10^6 g m^{3-} (of water))/0.1 m^2). A possible worst-case scenario is therefore that up to 1080 m, or ~1/3, of the drill fluid in the borehole could be displaced if 20 m of heavily clathrate-laden water were to be allowed to rise up the borehole.

[70] In this worst-case scenario, the following two effects could be seen at the ice surface as lake/clathrate-rich water gets into the borehole: (1) The water level in the borehole cavity will increase in an exponential manner and (2) if nothing were done, a runaway situation could occur, leading to borehole water and gas (air) escaping from the top of the borehole.

4.5. Inclined Roof of Subglacial Lakes Mitigates Clathrates Entering a Borehole

[71] The ice-water interfaces of subglacial lakes have notable slopes (~–11 times the ice surface slope), which in a worst-case scenario will offer some defense against clathrates entering the borehole provided the access hole is well placed. The slope of the ice-water interface of Lake Ellsworth is particularly steep, with a gradient of ~1 in 33 (see Figure 3).

[72] Clathrates heavier than lake water will not rise up the borehole. Even if they become unstable and degas, the gas will rise up the lake water column and, once at the ice water interface, will continue to travel upslope to the upstream end of the lake. The borehole presents a place where gas can escape, but the hole is minute compared with the wider lake surface, and even if some gas is transmitted to the borehole, it will have opportunity to redissolve in borehole water.

[73] Clathrates lighter than water will not necessarily rise up the borehole. As the lake has a tilting ice surface, any clathrates currently lighter than lake water will be located at one end of the lake. It will be possible for such material to enter the borehole only if the upper levels of the lake (for Subglacial Lake Ellsworth this volume is ~0.4 km^3) are completely saturated with clathrates. For Subglacial Lake Ellsworth, this is likely to take at least 114,000 years assuming the maximum rate of ice melting of 15 cm yr^{-1}. There is a possibility that the ice sheet underside is scalloped and that light clathrates may collect in such pockets. It should be noted that the RES data shows no sign of large-scale scalloping, and hence the volume of clathrate material within such features (undetected by RES and therefore small) will be low. If the borehole were to access the lake in a "scallop," there would be a possibility of a small volume of clathrate material entering the borehole.

[74] One might imagine that clathrates at the same buoyancy of lake water may travel up the borehole if the borehole is under-pressured with respect to the lake pressure. According to *Mckay et al.* [2003], however, this eventuality cannot happen, as clathrates are either lighter or heavier, depending on the level of CO_2 concentration.

4.6. Likelihood of Permanence of a Closed System in the West Antarctic Ice Sheet

[75] Over glacial cycles, the ice sheet surface is known to rise (glacial) and lower (interglacial). For West Antarctica, the glacial rise above modern levels is estimated to be as much as 300–400 m in the Ellsworth Mountains, close to Lake Ellsworth [*Bentley et al.*, 2010]. At the center of large ice sheets, the temperature of the deep ice is generally increased with ice thickness, and thus we expect expansion of the region in which basal melting takes during periods of full glaciation. This is confirmed by thermodynamic modeling of the Antarctic ice sheet, which indicates melting across the bulk of the WAIS during the Last Glacial Maximum [*Huybrechts*, 1990]. For Lake Ellsworth, even if the lake were closed today, broadening the basal melt zone would likely allow water to flow downstream. The implication is that Lake Ellsworth is unlikely to have remained as a closed system during glacial cycles even if it is at present.

[76] Postglacial ice sheet relaxation to modern levels in the Ellsworth Mountains occurred less than 10,000 years ago [*Bentley et al.*, 2010], and hence the maximum time available to be a closed system is likely to be <10,000 years. In this glaciological scenario, the lake is likely to be hydrologically open during >90% of the last glacial cycle, meaning clathrate buildup will not occur (as this takes at least 19,600 years) or, if it does, will not accumulate to a serious level (as it would take >100,000 years to be a problem).

4.7. Qualitative Summary of the Risks

[77] Geophysical data and understanding of ice sheet history and subglacial processes inform us that there are negligible risks on access to Lake Ellsworth from (1) water pressure–driven outpouring at the ice surface on lake access; (2) gas blowout due to hot-water drilling of meteoric ice; (3) blowout from gases in lake water, given an open hydrological system; and (4) blowout from lake clathrate gases in an open system.

[78] If the hydrological system is closed, however, we regard the risk of blowout from lake clathrate gases to be high if the system has been closed for 400,000 years, and if the melt/freeze rates are of the order of 15 cm yr^{-1}; the risk is low if the system is closed for 100,000 years and negligible if the system has been closed for the entire Holocene (Iast 10,000 years). If the melt/freeze rates were of the order of 4 cm yr^{-1}, the risks reduce considerably, to low, very low, and negligible, respectively.

[79] Clearly the probability of Lake Ellsworth being a closed hydrological system is a key factor in the analysis of blowout risk. Qualitatively, we regard the likelihoods of Lake Ellsworth being continuously closed for 400,000 years as very low, for the last 100,000 years as also very low, and for the last 8000 years as being moderate. We conclude, qualitatively, that the overall risk of gas blowout upon entry to Lake Ellsworth is very low.

4.8. Quantitative Assessment of Risk

[80] In order to quantify risk we need to clearly define it. Risk is a combined assessment of the probability and consequences of an incident. So there are three components to be considered in estimating the risk: the probability, the event to which the probability is attached (in this case, gas blowout), and the severity of the consequences (in the worst case, death).

[81] A formal judgment elicitation exercise was conducted [*Brito et al.*, 2012] to link expert judgments concerning the probability of blowout for six different scenarios and the probability of death due to blowout [after *O'Hagan et al.*, 2006]. The experts' judgments were mathematically aggregated in order to produce an assessment that would represent the group's view.

[82] On the basis of this quantitative risk assessment exercise, the estimated probability of blowout upon accessing the surface of Lake Ellsworth is lower than 1.23×10^{-3},

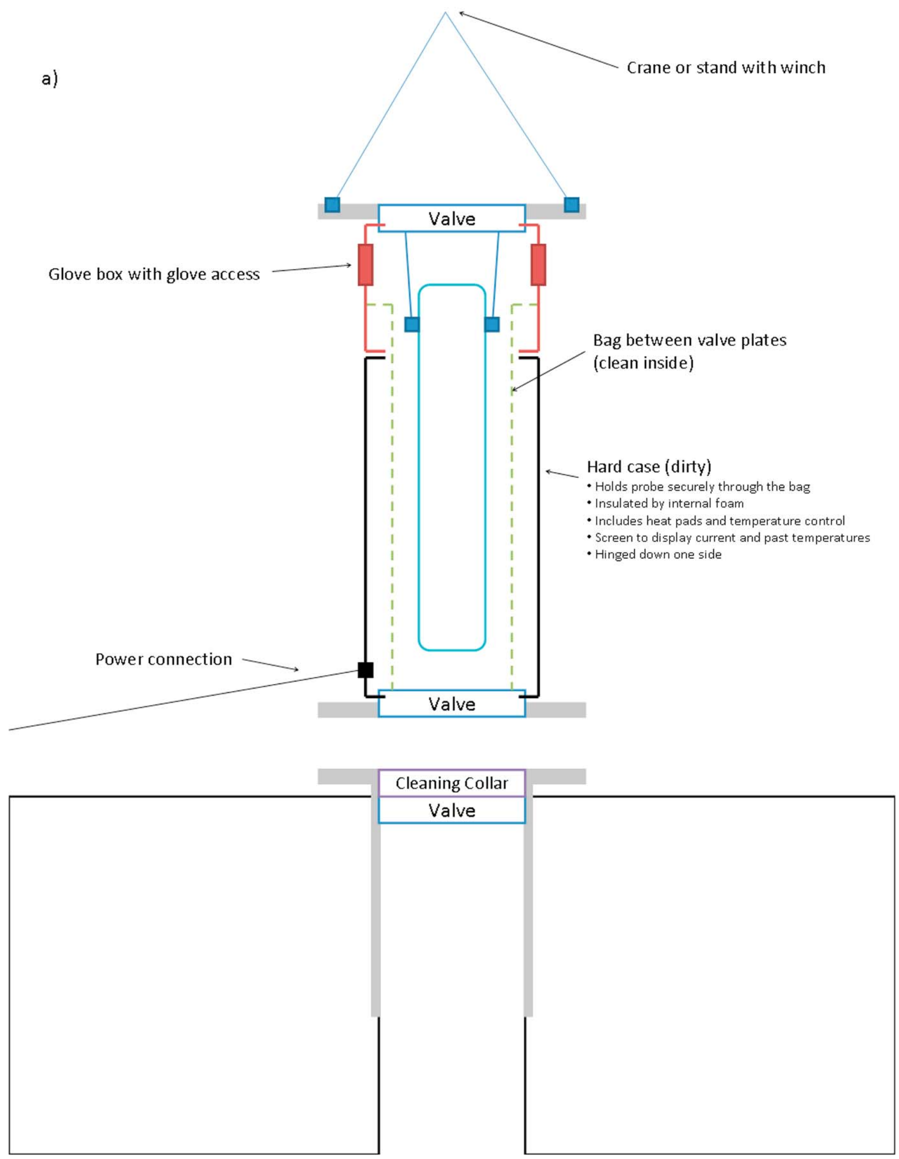


Figure 7. Twelve-stage sequence for deploying the scientific instruments. (a) Probe is positioned over wellhead. (b) Probe valve is mounted on wellhead. (c) Hard case is unclipped and removed. (d) Probe is lowered into hole. (e) Lifting winch/crane is detached. (f) Container moves into position. (g) Container is over wellhead. (h) Glove boxes are mated. (i) Tether is mated to probe. (j) Tension is taken up by main winch. (k) Securing wires are detached. (l) Probe is lowered to lake.

with 95% confidence. This value reflects the probability of blowout, not the actual risk of death due to blowout. Risk to life is an area covered in length in the Health and Safety Executive (HSE), UK, documents (see http://www.hse.gov.uk/risk/theory/r2p2.pdf and http://www.hse.gov.uk/nuclear/tolerability.pdf). The HSE sets a tolerable risk (TR) for employee death per annum to 10^{-4}. If blowout meant certain death, then the risk of blowout would have been unacceptable. However, if a blowout takes place, the scientists will have enough time to put in place a structured evacuation plan, leaving the drill site to a safe haven at least 100 m away. Thus, in this case, blowout does not mean certain death. The quantitative assessment of the probability of death due to blowout given that a structured evacuation is put into place led us to an estimated risk lower than 8.96×10^{-5}, with 95% confidence. This is lower than the tolerable risk specified by the HSE. As a result, potential engineering methods to mitigate blowout are not considered necessary.

5. DEPLOYMENT OF INSTRUMENTS IN THE LAKE

[83] Upon successful access of Lake Ellsworth by the hot-water drill, instruments will be sent into the lake to measure and sample the environment. Here we provide information on the equipment required to test the program’s hypotheses, including technical specifications, plus descriptions on how the equipment will be used, the samples collected, and the

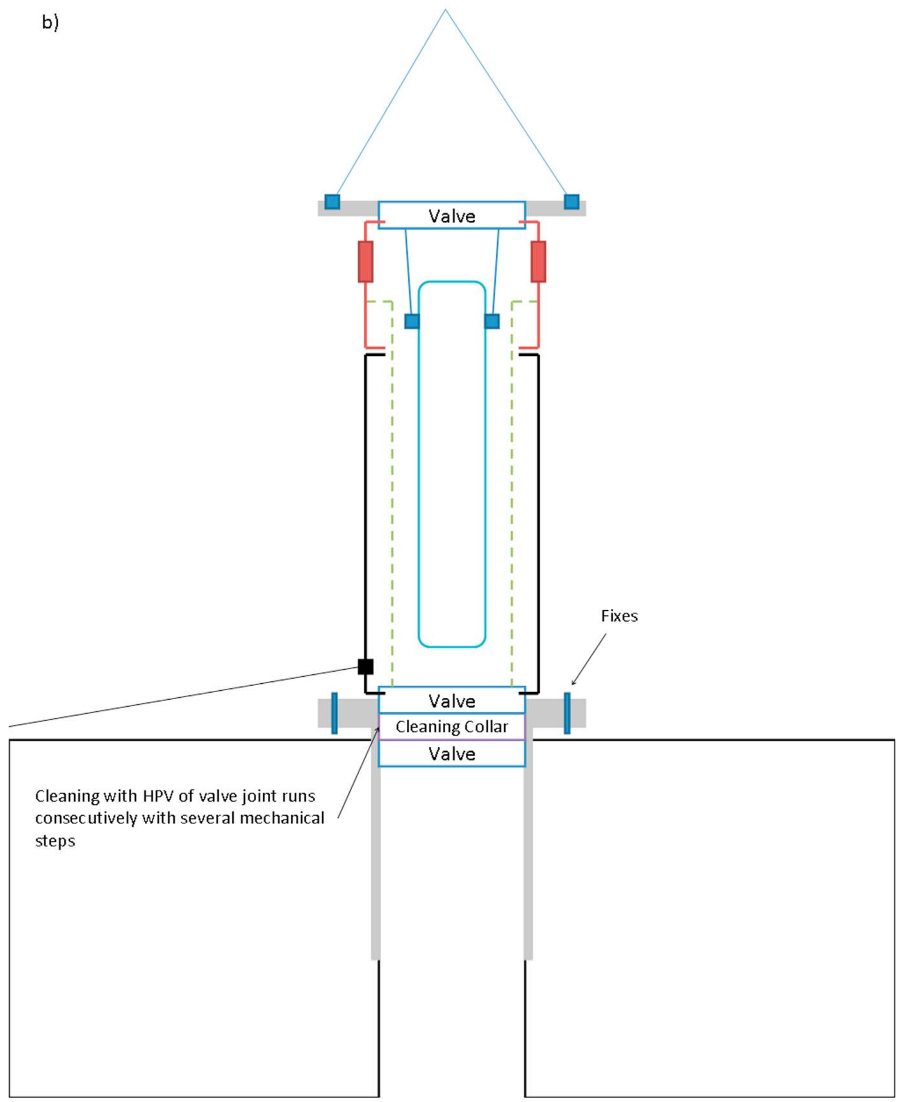


Figure 7. (continued)

subsequent laboratory analyses. Particular emphasis is given to the methods used to sterilize the equipment to ensure levels of cleanliness that will be crucial to the success of the science being conducted and for environmental protection. Such methods are compatible with the NAS-EASAE report and the SCAR code of conduct on subglacial access.

[84] Sampling of lake material (water and sediments) will be conducted by a purpose-built lake probe and sediment corer. The probe and corer will be contained in transit cases for protection during transport and installation. Both instruments will be cleaned and sterilized inside a plastic bag suspended between valves (details about cleaning and sterilization are given in section 7). Clean deployment of the instrumentation, key to ensuring cleanliness of the entire mission, is shown pictorially in Figure 7 and described as follows. The transit cases will be suspended from a crane and connected to the head of the wellhead. While suspended, the hard outer case will be removed. The probe or corer is then lowered onto its glove box support and the plastic protective bag around the probe will be concertinaed. The crane support is then removed. The deployment container is wheeled into position. The glove box is then connected to the sheave within the container. The connecting valves are opened and the probe/corer connector is married to the tether. The tension is taken on the tether and the probe/corer support is removed. The probe/corer is then lowered into the hole. The process is reversed to recover the instruments. The drill, probe, and corer are all deployed and retrieved separately. The use of the cleaning collar (and other microbial control methods) reduces the risk of contamination being introduced during deployments.

5.1. Probe Description

[85] Preliminary designs for the probe and its systems have been completed by the National Oceanographic Centre (NOC) in collaboration with the Lake Ellsworth Consortium over the past 4 years. These designs have been being refined by the

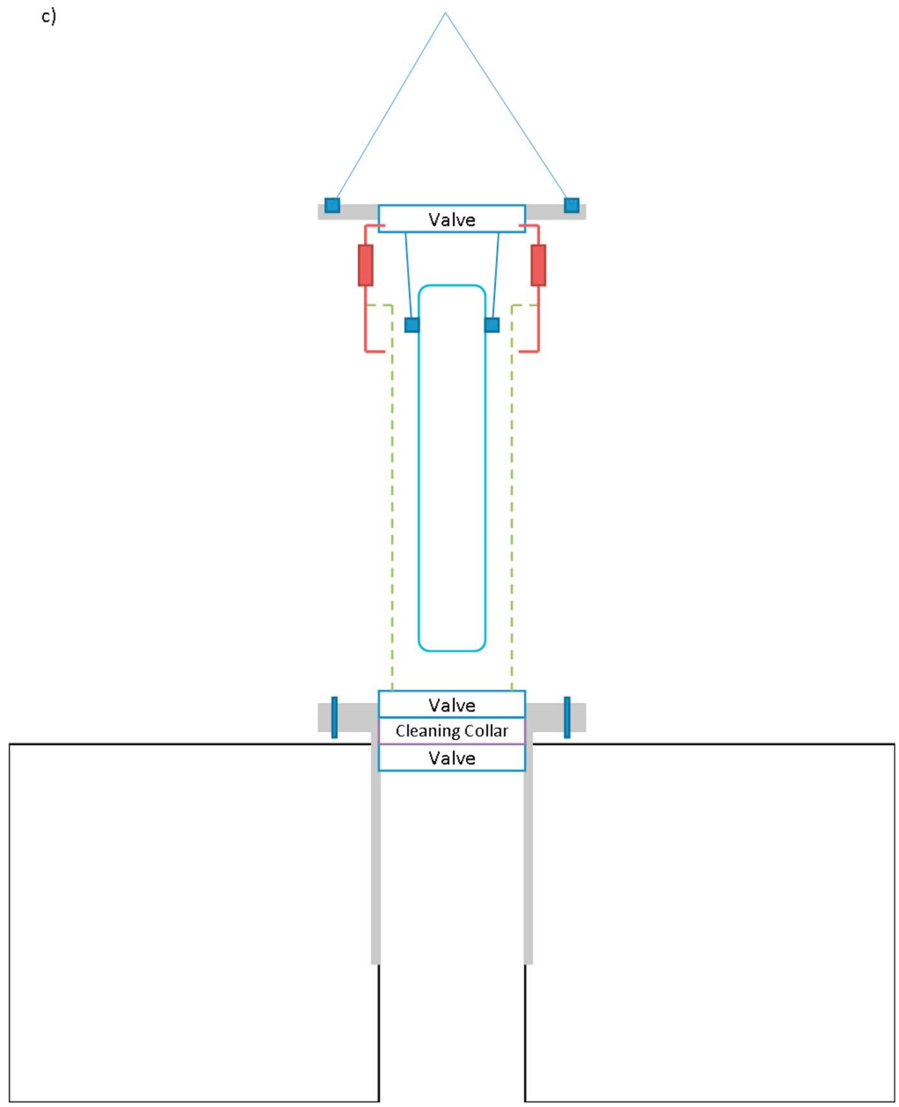


Figure 7. (continued)

program (including design and testing in an oceanographic setting) to produce two identical probes (for contingency).

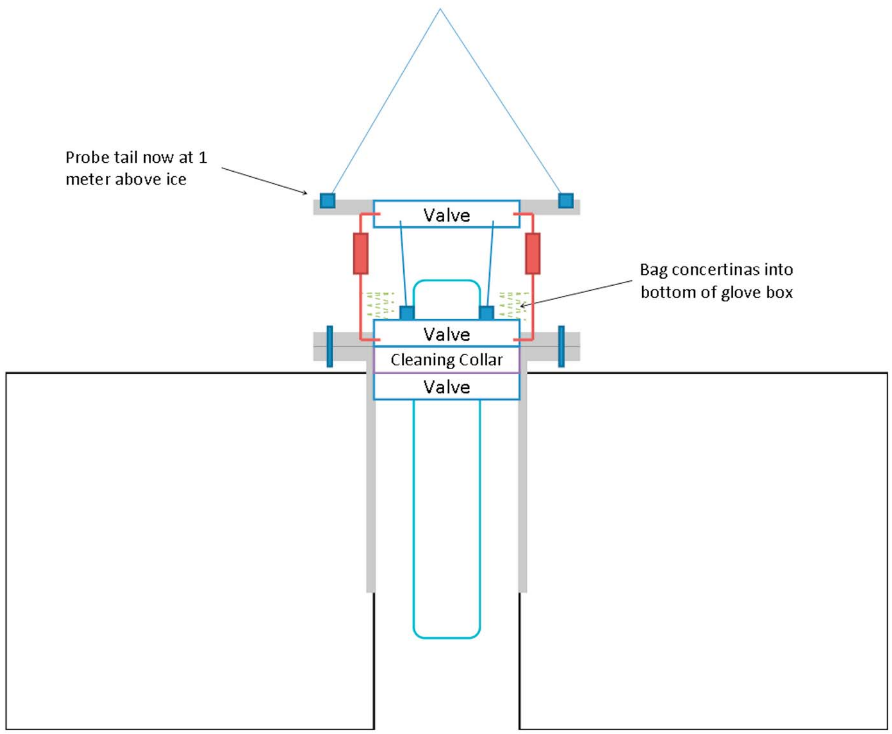
[86] Each probe consists of two pressure cases. The lower contains the majority of the instrumentation, and the upper contains the power and communications demodulation systems. These two vessels are separated by water samplers (Figure 8). Data are returned in real time, enabling informed operation of the sampler systems. Water and sediment samples will be recovered for postretrieval analyses.

[87] An onboard microprocessor and data logger will enable continued operation (e.g., sampling at predetermined intervals) and archiving of instrument data in case of communications failure. Power will be supplied both through the tether and by onboard batteries, the latter being sufficient to complete the mission. Probe-to-surface communications (two-way) will be via an optical link and backup wire modem using commercial off-the-shelf (COTS) technology used in several deep-sea remotely operated vehicles.

[88] The probe includes three rosettes of eight bespoke 100 mL titanium bottles (designed to withstand the high pressures generated when the water sample freezes at the surface following recovery of the probe). The use of titanium is a requirement for trace metal (e.g., Fe (II)) analysis. The sampling bottles can collect water at any time or depth (to be specified by the science program or in response to in situ measurements; see section 6.1). Each bottle can be flushed by several liters of water before capturing a sample (which will take 30 s). The bottle valves are actuated using magnetically coupled electric motors enabling them to be opened and closed on demand. Samples are maintained at pressure, enabling quantitative analysis of dissolved gases. Each container with its two valves is detachable from a carousel frame for processing and storage. Each of the carousels has two rotary pumps (providing an important level of redundancy) fitted to a manifold to flush the tubes with sample.

[89] In each rosette, seven of the bottles will be opened once immersed in the borehole. This significantly eases the

d)



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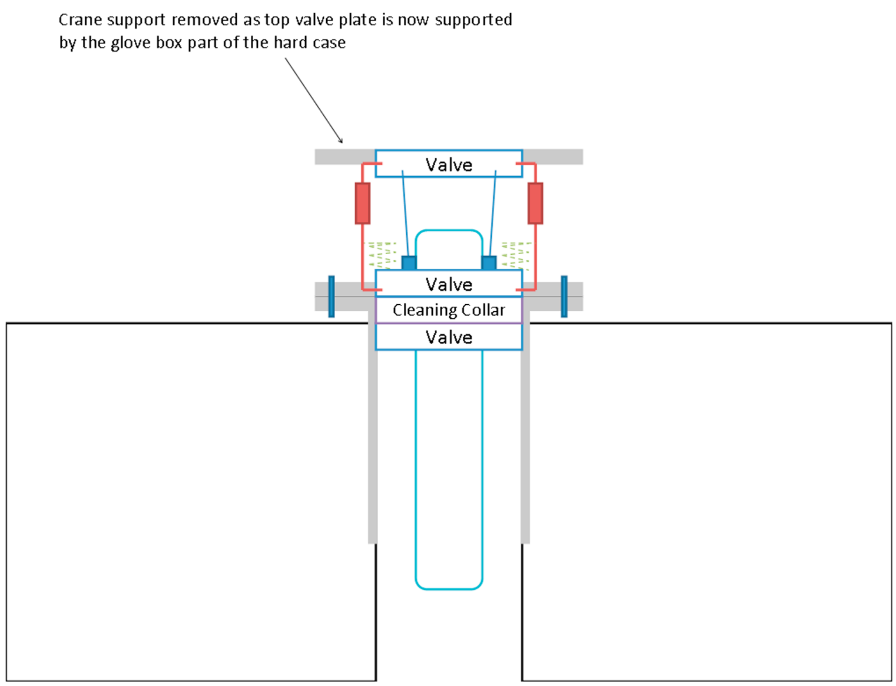

Figure 7. (continued)

problem of bottle opening at depth. The remaining bottle will contain sterilized water and will be heated to prevent freezing while in the borehole and lake. This bottle will act as a control sample. After capturing a sample, each bottle will be sealed from the environment and opened after surface sterilization in a closed sterile microbiological cabinet.

[90] The sampling method used maintains the in situ pressure of the samples, preventing outgasing on return to the surface. This means that the samples are pressurized on

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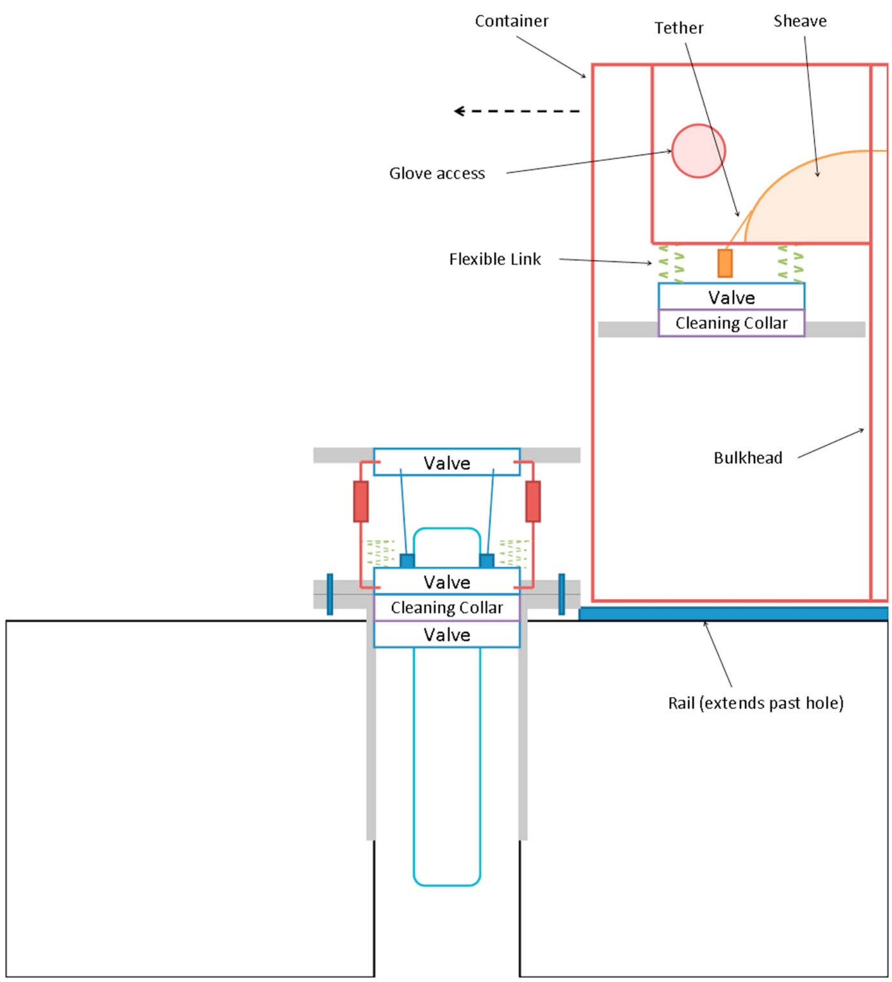

Figure 7. (continued)

return to the surface, allowing analysis of gas content. This will be completed using a bespoke degasing system (that will analyze the evolved gas as the samples are depressurized). Gas contamination will be minimized by purging and evacuation of valves and interconnecting pipes.

[91] Independent of the water samplers, each sampling rosette contains two 0.2 μm filters, which will be used to extract filtrand from ~100 L of lake water (taking around 30 min to do so). The filter papers will be allowed to freeze at the surface and will be split and packed for immediate microscopy analysis at Rothera Station and, later, at U.K. laboratories for more detailed work.

[92] The tip of the probe will be equipped with a narrow-diameter (25 mm) push corer. This will sample a few centimeters of sediment from the lake floor, including the crucial sediment-water interface. In ultraoligotrophic lakes this interface is often the site of the highest abundance of life in the lake and so is a key target. Moreover, the use of a corer on the probe provides a level of redundancy for the main percussion corer. The probe mounted corer will be sterilized before deployment and samples capped in the sterile wellhead on retrieval.

[93] The probe will be equipped with >6000 m rated commercially available sensors to measure pressure (P), temperature (T), conductivity (EC), oxygen concentration (electrode) (DO), redox potential (Eh), and pH. A video camera and sonar will provide additional information on the lake environment. Redundant temperature, conductivity, and oxygen (optode) sensors will also be installed to increase reliability. The instrumentation will be attached to the main body and at the front of the probe.

[94] A ranging sonar with an 80 m active radius will be mounted on the forward face of the probe. A second sonar will be mounted on the rear end of the probe, enabling ranging to the underside of the ice. Underwater video will be supplied with two video and light packages, one at each end of the probe allowing imaging of both the lake bed and the borehole and underside of the ice. These will store data locally and transmit at high fidelity via the optical communications link.

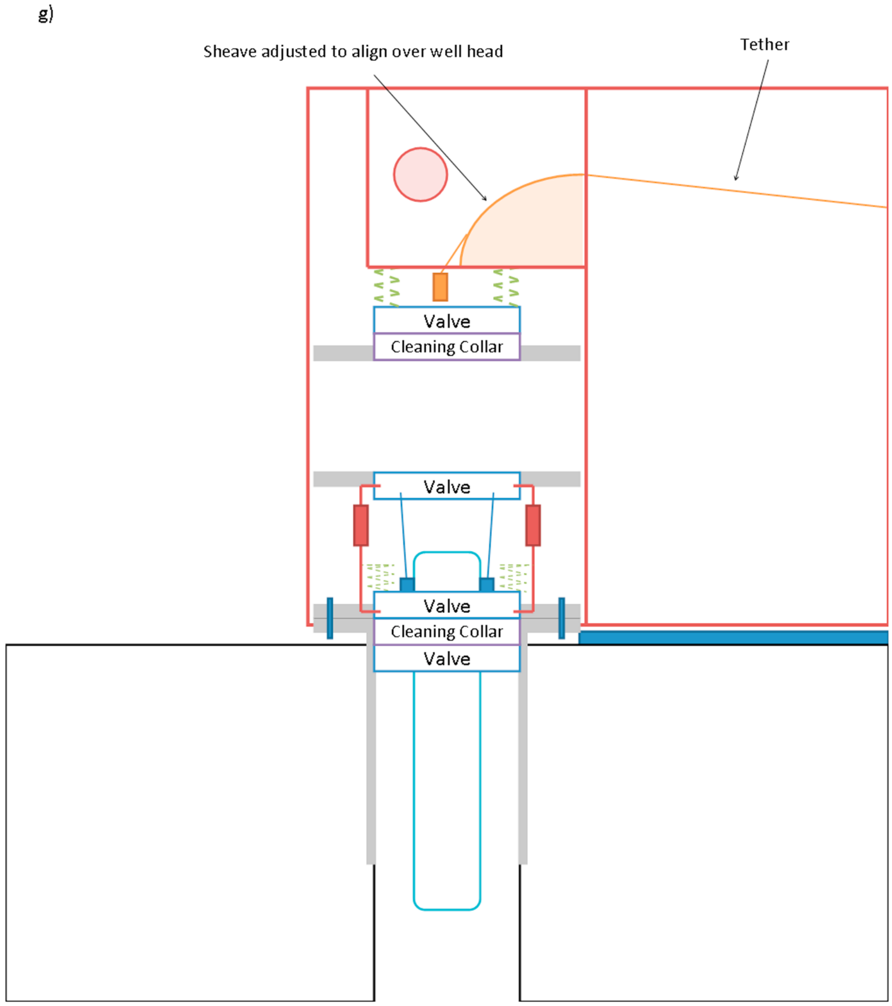

Figure 7. (continued)

5.2. Topside Equipment

[95] A winch system suitable for both the probe and the corer has been developed and has the following specification: a spool, a top sheave, a render (clutch) system, power converters and slip rings, optical and electrical communications pickup, and interface to the cleaning collar (Figure 7). The tether is of synthetic composite construction and includes four copper conductors for power (2.5 mm^2), two copper conductors for backup communication channels, and six optical fibers. The tether is sheathed in a flexible jacket to facilitate easier on-site sterilization and cleaning. Command, control, and data logging will be supplied by a dedicated and redundant computer-controlled system housed in a topside tent.

5.3. Sediment Corer

[96] Sediment coring at several-kilometer water depth is common in the world's oceans. The technological challenge is to develop existing designs to enable sterilization and cleaning, diameter reduction for deployment down the 30 cm wide borehole, a significant reduction in weight, accurate positioning of the corer at the sediment water interface, and a percussion system for driving the core tube past a fixed piston into the sediment.

[97] A percussion driven piston corer is being designed and manufactured by BAS and UWITEC (an established limnological engineering company based in Austria), who have previously developed corers to recover sediments successfully from beneath the George VI Ice Shelf and the WAIS.

[98] All aspects of the corer are designed to facilitate cleaning and sterilization (using the same procedures used for the probe). The precleaned corer will be stored in a transit case with a sterile bag that will be removed, prior to deployment, at a few meters depth in the borehole. The corer and all its components will be cleaned in a similar manner to the probe. After probe retrieval, the corer will immediately be deployed via a similar transit case and on the same tether as previously used for the probe. This will minimize costs, logistical effort, and the changeover time between devices. The corer will be lowered to the lake floor and precisely positioned, and then a hollow core barrel will be hammered into the sediment past a fixed piston by activating a percussion hammer. This operation will be controlled by the

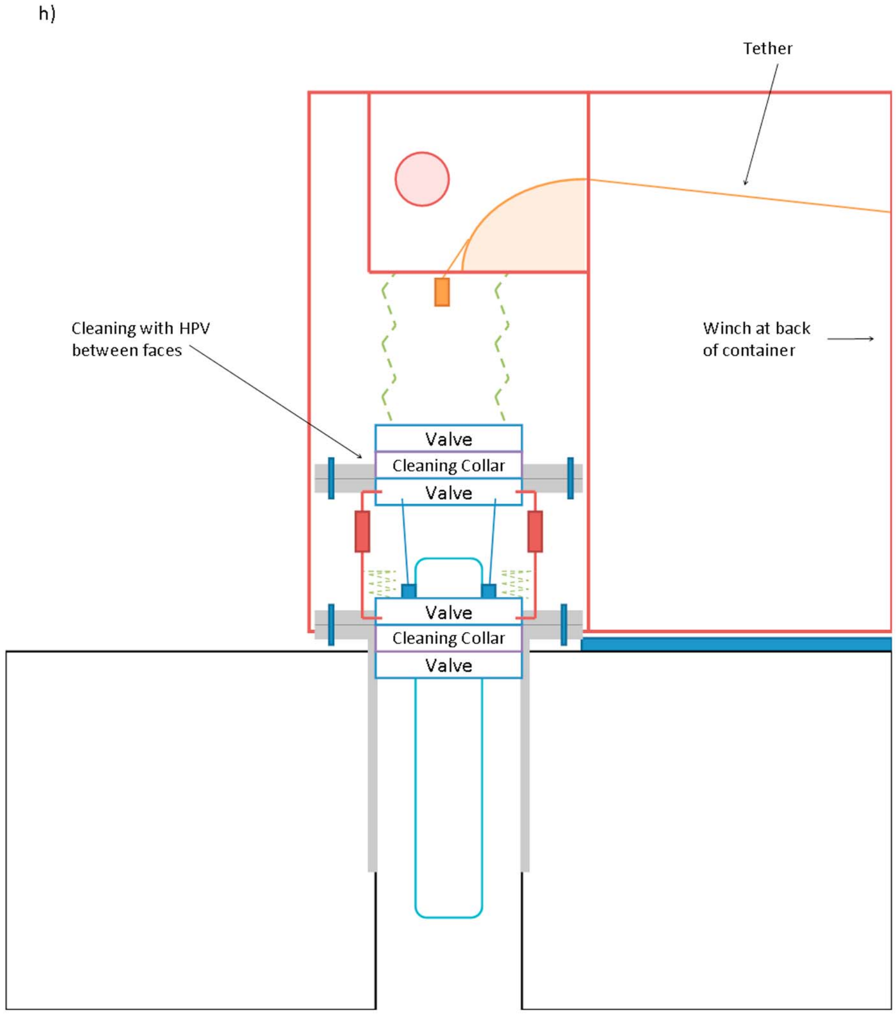

Figure 7. (continued)

sensor package on the corer connected to a corer control unit on the surface located within the heated working space.

[99] We anticipate penetration to ~1–3 m depth, but this will be dependent on composition (e.g., grain size) and water content of the sediment. Penetration of the core barrel will be monitored and when no further penetration is achieved, the corer will be allowed to settle and then be retrieved by winch to the surface. During retrieval the piston will be locked in place via the piston rod lock, which, along with a core catcher at the lower end, will retain the sediment in the core barrel. When the core reaches the surface it may already be partly frozen. In advance of freezing, subcores will be handled vertically in order to preserve their stratigraphic integrity and paleomagnetic properties.

6. SAMPLING AND ANALYSIS OF SAMPLES

[100] Once equipment is inserted into the lake, a clear understanding of how samples will be collected is required, based on measurements taken of the lake, not least because of the short (<24 h) period available. Here we outline the protocols to be followed (particularly for the probe) and the subsequent laboratory analyses of the samples taken.

6.1. Water Sampling Strategy

[101] The rate of probe descent in the lake will be 1 m per 30 s. Thus, water collection within one 100 mL bottle will sample ~1 m of the water column, unless the probe is halted during sampling. We will take samples in triplicate (activating three bottles each time) for bioassay, hydrochemistry, and organic geochemistry. This sampling approach gives us flexibility for reallocation of samples if (1) some are contaminated during the collection process or later, (2) first analyses indicate that the water is so dilute that samples must be combined to achieve detection, or (3) unexpected results indicate the desirability of additional analyses.

[102] Usual practice in deep oceanographic and limnological sampling is to log the properties of the water column on descent and to use this information to define sampling locations on ascent. In our case, it is prudent to collect samples on descent because there is a risk (albeit low) of being unable to sample on ascent (due to rupturing of the communication tether during retrieval of sediment). With this in mind, we will

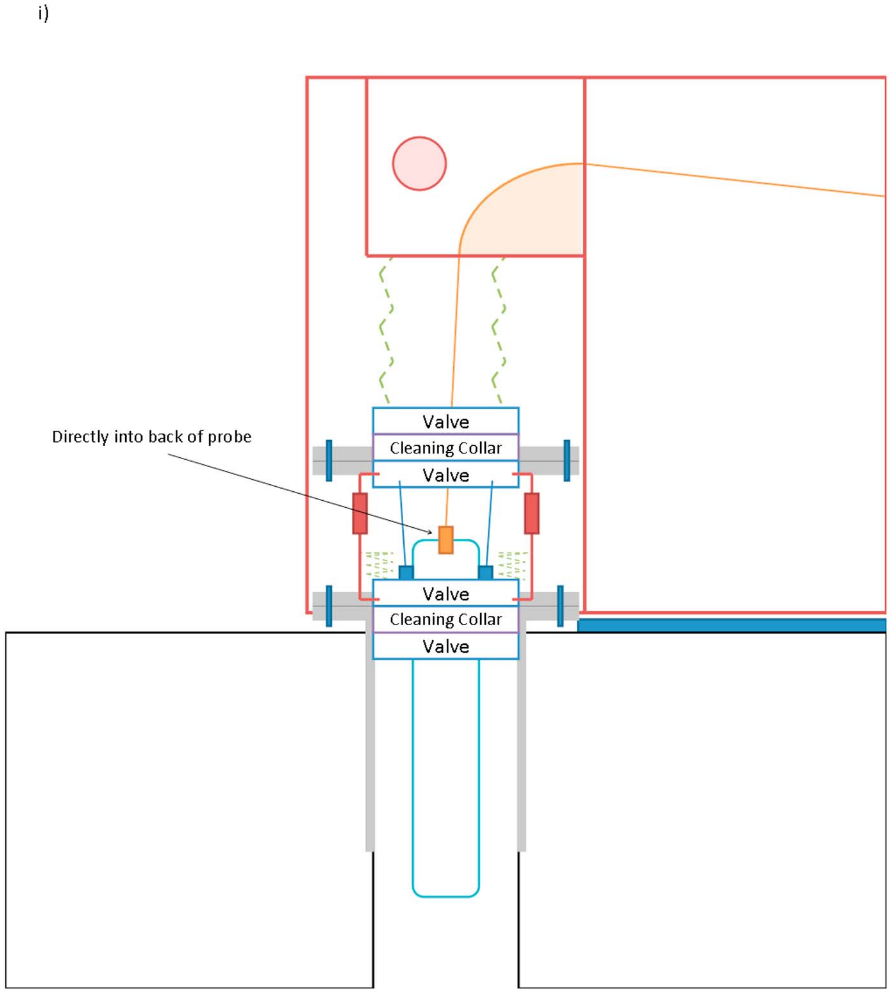

Figure 7. (continued)

collect samples during initial descent at water depths of 10 m, 50 m, 90 m, 130 m, and 140 m (i.e., 3 m from the lake floor). Measurements (P, T, EC, DO, Eh, and pH; see section 5.1) taken during descent will inform us whether the remaining samples should be taken at specific locations of scientific interest (i.e., at sharp temperature/chemical gradients) or at depths of 110 m, 70 m, and 30 m (completing the water column sampling at a 20 m spacing). If necessary (e.g., if the chemical and physical stratigraphy of the water column is complex), all sample bottles can be flushed and refilled at any lake depth. In addition to the samples collected in the lake, control samples of the borehole water will be collected at regular (30 min) intervals during the drilling program to determine background levels of biological and chemical parameters.

6.2. Analyses

[103] The probe will deliver information concerning physical, chemical, and biological properties of the lake's water column. Appropriate scientific expertise will be present in the field to (1) manage the probe's sampling strategy and (2) interpret the probe's results to comprehend the environment of Lake Ellsworth. Data collected by the probe will be recorded on site and made available to project members in the first instance, and later to the international scientific community. First analysis, on the filtrand recovered by the probe's water pumps, will take place in laboratories at Rothera Station. The rest of the material recovered will be packaged into sterile containers and transferred to U.K. laboratories where detailed analysis can take place. Four independent laboratory analyses of lake-sample material will be undertaken, and these are summarized below.

[104] Direct measurements of the lake's water column (taken by the probe) will be compared with laboratory results from the water and sediment samples to form a comprehensive evaluation of the physical, chemical, and biological conditions and processes within Lake Ellsworth. This integration will also involve analysis of the sediment cores, to understand how modern conditions in the lake may have differed in the past.

6.2.1. Microbiology

[105] The objective of the microbiology work package is to use well-tested but cutting-edge laboratory analyses to document the nature of microbial life in Lake Ellsworth.

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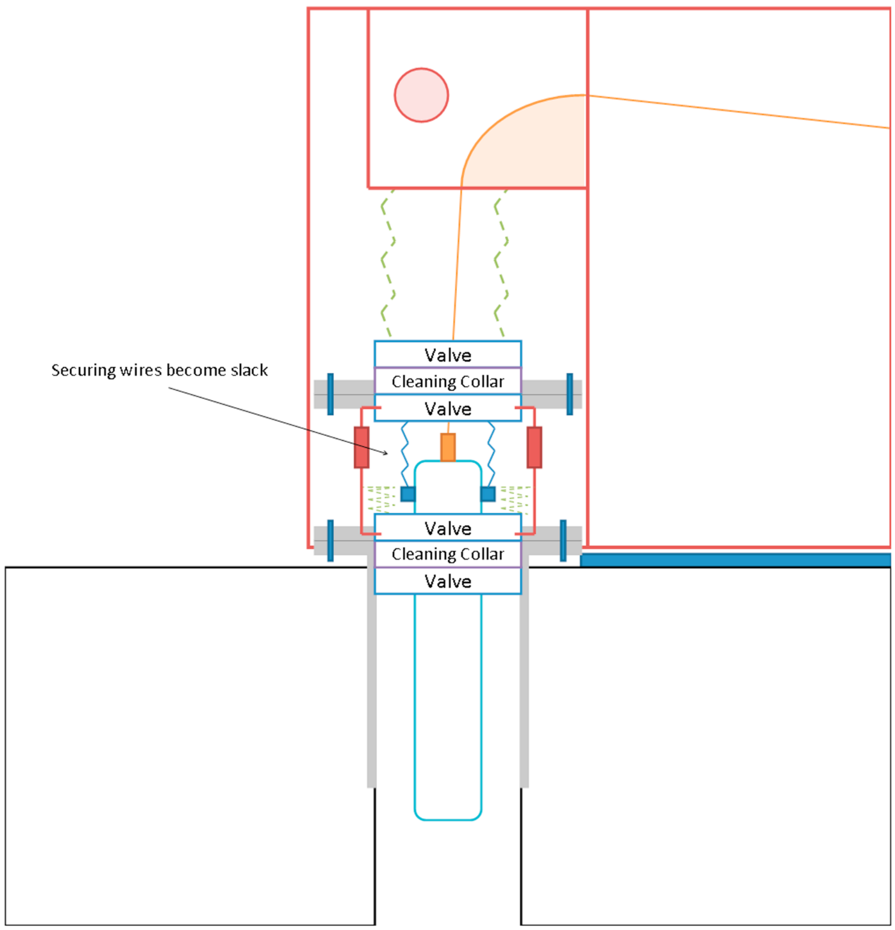

Figure 7. (continued)

Lake samples, borehole samples (time series of drilling fluid), and surface ice samples will be studied to investigate the microbial biodiversity present and to prescribe studies for potential contamination. We will measure life within Lake Ellsworth through (1) microscopy, (2) biochemistry, and (3) *molecular biology* (Table 2).

[106] A combination of microscopy, biochemical, and molecular biological techniques will be used to study samples in clean laboratory facilities to determine the abundance, distribution, and diversity of microorganisms in the lake. We will use standard microbial quantification techniques, such as nucleic acid staining (DAPI, SYBR Green, SYTO 9) to obtain microbial numbers. The following three laboratory approaches will be used to investigate microorganisms within samples retrieved: (1) Microscopy; fluorescent (used with specific gene probes) and electron microscopy. (2) Biochemistry (biogeochemical cycling); in the absence of light, the microorganisms within Ellsworth must be using either organics or inorganic redox couples to gather energy. We will assay the water/samples for the presence of genes involved in biogeochemical activity. (3) Molecular biology; genomic DNA will be extracted from material obtained and used to construct a metagenomic library to screen for novel physiologies and phylogenies.

6.2.2. Organic Geochemistry

[107] The objectives of the organic geochemical analysis are to characterize the organic chemistry of the water (i.e., what compounds are present, regardless of origin), to determine compounds indicative of, or capable of, supporting, biological activity and to test for contamination. The restricted sample volumes from Lake Ellsworth will require different methods of analysis from more typical experiments where sample volumes are unlimited. The analytical techniques to be used include *gas chromatography–mass spectrometry* (GC-MS) and *high-performance liquid chromatography* (HPLC).

[108] The GC-MS will determine several different types of compounds, including phenols, alkylphenols, polyaromatic hydrocarbons (PAHs), fatty acids, and alcohols. Many organic compounds in natural waters reflect biological activity, but in very small samples we will focus on the more abundant types, especially fatty acids and fatty alcohols, including sterols. Amino acid concentrations will also be determined.

[109] The HPLC work is best suited for water-soluble compounds (which are not suited for GC-MS). Using a

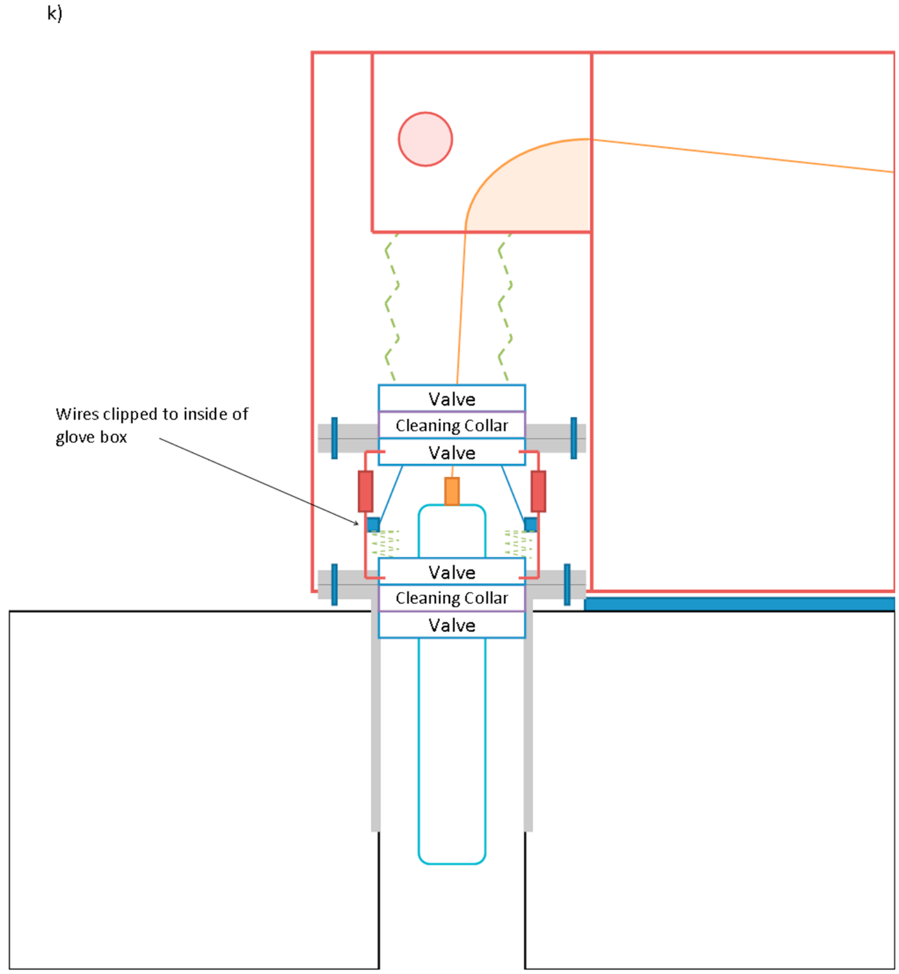

Figure 7. (continued)

coupling of HPLC to ICP-MS (inductively coupled plasma MS), we will target compounds, including heteroatoms, that may be markers of biological activity, especially organosulphur and organophosphorus compounds, variations in which can be compared against fluctuations of inorganic sulphate and phosphate in the same samples. The approach can also detect organometallic compounds such as porphyrins that are widely found in biological material [*Raab et al.*, 2003].

6.2.3. Hydrochemistry

[110] The objectives of this work package are to compare the water chemistry of Lake Ellsworth with that of the incoming ice melt (as in section 2.4) to determine the following aspects of the physical, chemical, and biological properties of the lake: (1) the residence time of the water and the nature of circulation and stratification; (2) the dominant geochemical processes, (3) the nature of biogeochemical reactions, and hence (4) geochemical indicators of life.

6.2.4. Sedimentology and Paleoanalysis

[111] The sediment sequence beneath Lake Ellsworth is likely to contain an admixture of subglacially eroded sediment and dust from the ice above. On the basis of the seismic evidence that demonstrates sediment thicknesses of >2 m, it is likely that subglacially eroded sediment is the dominant component (estimates of *eolian dust* concentrations in the overlying ice are too low to produce this order of sediment thickness). An array of sedimentological analyses will be applied to the sediment core from Lake Ellsworth for life detection, core dating, and paleoenvironmental reconstruction: Many of these have been tested on Hodgson Lake, a subglacial lake that emerged relatively recently from a retreating margin of the Antarctic Peninsula Ice Sheet [*Hodgson et al.*, 2009a, 2009b].

7. IDENTIFICATION OF IMPACTS AND PREVENTATIVE MEASURES

7.1. Methods and Data Used to Predict Impacts and Mitigation Measures

[112] To allow the assessment of the environmental impacts associated with the exploration of Lake Ellsworth, relevant information the lake's environment, and the technique used to explore it, has been gathered. Here we discuss how the program might alter the baseline environmental conditions (i.e., the potential environmental impact) and how such an impact will be mitigated. In addition to site and program specific data, special consideration has been given to relevant guidance and codes of conduct documents [*Committee for Environmental Protection* (*CEP*), 2005; *U.S. National*

l)

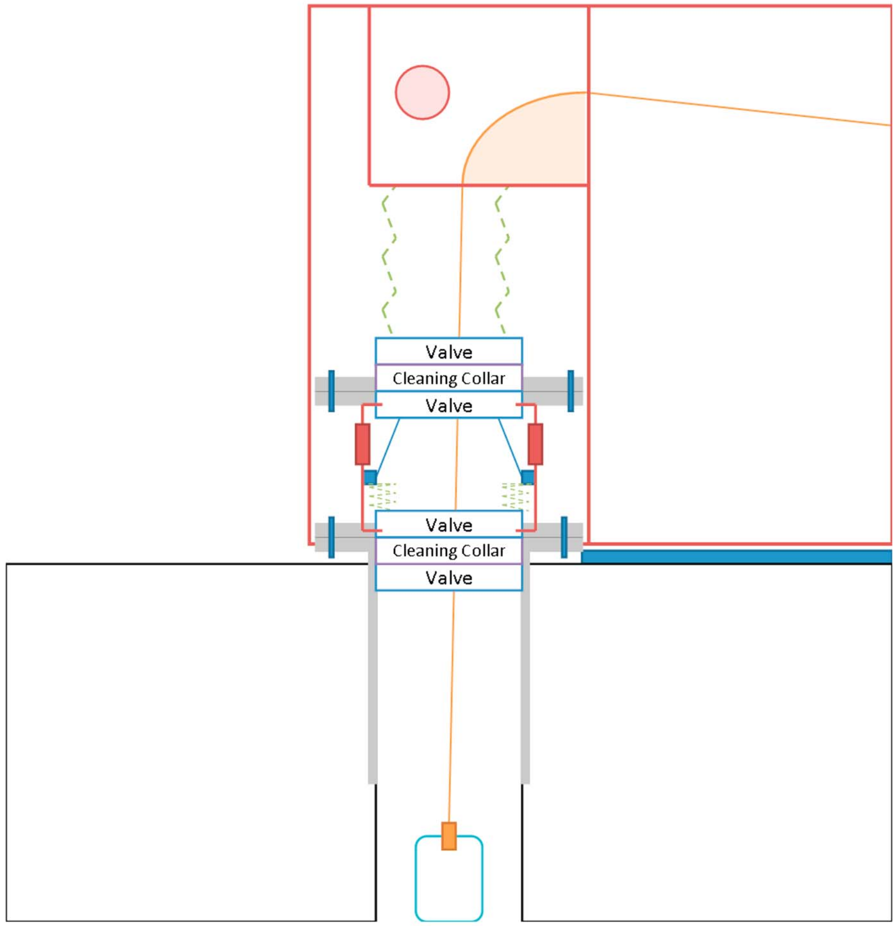

Figure 7. (continued)

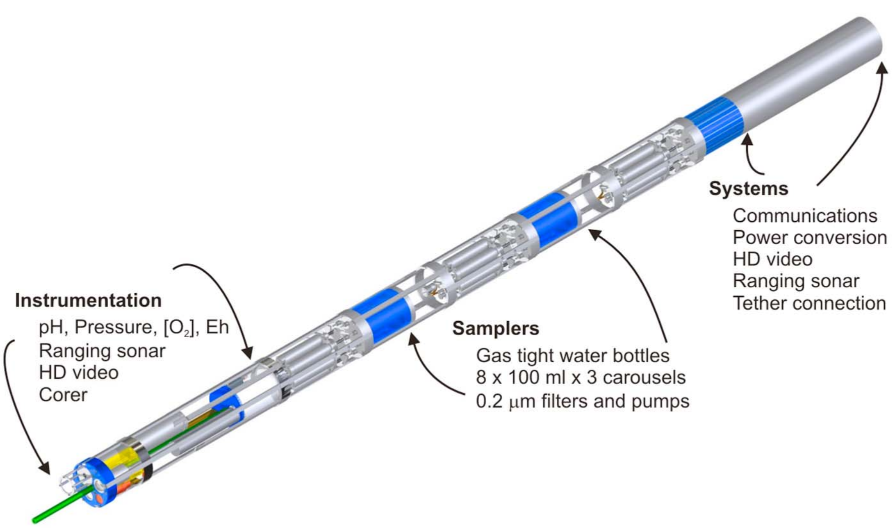

Figure 8. Illustration of the probe concept and its instrument and sampling arrangement. The probe's dimensions are approximately 4500 mm in length by 200 mm wide. The probe has two casings, above and below the sample chambers, to house the instruments and systems, respectively.

TABLE 2. List of the Microbiological Analyses To Be Undertaken on Lake Ellsworth Water Samples

Microbiology Approach	Detection Methods
Microscopy	specific stains (×5), SEM and TEM
Culture	10 × 384 well plate 10 μL per inoculum
PCR	clone library, RT-PCR, Q-PCR
FISH	10 group specific probes
Environmental genomics	metagenomics/whole genome
Biomarkers	radiotracer 2 mL × 5 per assay

Research Council, 2007; *Alekhina et al.*, 2011] that collectively summarize proposed best practice principles for drilling, lake entry, sampling, and instrument deployment.

[113] The environmental impacts of this proposed program are predicted on the basis of professional opinion and judgment. Direct, indirect, cumulative, and unavoidable impacts are examined. Where impacts are predicted, measures to mitigate or to prevent those impacts are identified and discussed. It is recognized that all activities must be carried out in strict compliance with the Environmental Protocol and will be subject to a permit issued by the UK Foreign and Commonwealth Office under the Antarctic Act (1994). Other programs will have similar official permitting procedures with which to comply.

7.2. General Principles

[114] Lake Ellsworth is a pristine aquatic environment, and it is imperative that possible damage and contamination during its exploration be minimized or eliminated. There is currently no knowledge on the presence and type of any life forms within Lake Ellsworth, but it is hypothesized that the lake contains unique microorganisms adapted to the extreme environment.

[115] Microbial communities and naturally occurring mechanisms of introduction are discussed in the NAS-EASAE report, which states that "Many potential mechanisms exist for bacterial dispersion…about 10^{18} viable microbes annually are transported through the atmosphere between continents…. Of particular importance to the study of subglacial aquatic environments is their potential connectivity, which may allow the movement of microbes beneath the ice sheet…. The surface of the Antarctic ice sheet acts as a vast collector for microbiota deposited from the atmosphere, global ocean currents [and] birds…a subset of this microflora may retain viability and even metabolize within the snow and glacial ice. These communities of viable cells and spores may ultimately reach the subglacial aquatic environments to provide a continuous inoculum at the melting glacier ice-lake water interface" [*U.S. National Research Council*, 2007]. This statement is significant because it indicates that the endogenous microflora in the overlying ice will have wide geographic origin and may be entering the lake through natural processes.

[116] The NAS-EASAE report also refers to the microbiology in Lake Vostok, where "Reporting on the microflora in ice cores from Lake Vostok [*Abyzov*, 1993] points out that in the deepest ice he examined (2405 m) only spore-forming bacteria remained." This implies that while the microflora in surface ice may be global in origin, the community structure has changed during transition to deep ice.

[117] The introduction of nonnative microorganisms, which have the potential to alter the lake's native populations, must therefore be prevented to protect both the environment and the scientific value of the exploration. This is especially important to protect not only the native microbial biodiversity of Lake Ellsworth but also that of any subglacial aquatic habitat down gradient of the lake.

[118] We recognize that the greatest environmental impact associated with the program is the potential to introduce microbial life into the subglacial environment. As a consequence, we have integrated environmentally protective measures throughout the program design. In particular, microbial control is central and dominant in the design process. Protective measures include the selection of the drilling method with the least potential for contamination (Appendix A), the use of cleaned melted ice in the drill fluid, and careful cleaning of all the engineered systems.

[119] The hot-water drilling system, using melted ice water as a drill fluid, heated to at least 90°C, filtered to 0.2 μm, and UV treated, minimizes the potential for contamination by dead or viable cells. Further protection is given by the cleaning and sterility methods, i.e., microbial control applied to engineered equipment, and is discussed further below. It is noted that the ideal program design would involve achieving complete sterility for all equipment and drilling water. However, it is accepted that sterility, as an absolute value, is not always possible or even verifiable.

[120] Currently, there are no detailed, published cleaning protocols for microbial control that could be directly applied, and so a task group was formed within the program to discuss and decide on an appropriate set of standards to adopt. The task group reviewed and recommended applicable protocols (e.g., from space and pharmaceutical industries and the U.K.'s National Health Service for surgical procedures) for well-established cleaning techniques that could be applied, and devised working standards and microbial control methods that would enable the principles recommended by SCAR and NAS-EASAE to be met.

[121] The following three standards have been applied, to get as low a cell threshold as is possible:

[122] 1. The general principle is a target of no measurable microbial populations to be present on any engineered structures in contact or communication (i.e., the probe, tether, sediment corer, and thermistor string if deployed) with the subaquatic environment.

[123] 2. All engineered structures must be checked, after manufacture and once ready for shipping, to determine any presence of microbial populations (i.e., that the principle above is being met).

[124] 3. In addition to the above, once the engineered structures are in the field, they must be subject to a method of microbial control that has been proven to work (through previous U.K.-based laboratory trials).

[125] These standards can be met through the application of a range of microbial control methods which, when coupled

with the hot-water drilling method, reduces the risk of contamination of Lake Ellsworth significantly.

[126] Different categories of microbial control have been used in the different stages of program, from program design, construction and deployment of the equipment, and microbial population reduction methods (i.e., removal and destruction of organisms on experimental apparatus). Our effort is focused on equipment that is in direct communication with the lake through the ice borehole (i.e., the wellhead, consisting of a borehole liner, UV collar for sterilization, and gate valves to provide an air lock; the sheaves used to lower equipment into the borehole; the hot-water drill hose and head for creation of the borehole; the probe used to make measurements and take samples, and its tether; and the sediment corer).

7.3. Microbial Control at Design Stage

[127] To improve the efficacy and extent of application of the methods there are a number of steps that can be taken during engineering design of the sampling equipment used. The first step involved materials selection for the probe and sampling equipment. In general, hard materials (e.g., titanium) are easier to clean than those with thick oxides (aluminum) or soft materials (elastomers and rubbers, which may be porous). Titanium is therefore used extensively on the probe. This simplifies microbial control and also enables trace iron analysis and reduces the thickness of load-bearing structures, giving more room for ancillary equipment. Samples of all candidate materials have been exposed to cleaning and the population control measures to identify any material degradation and the efficacy of these treatments. Using *hydrogen peroxide vapor* (HPV), we have demonstrated a reduction of log-6 for spore-forming bacteria *Geobacillus stearothermophilus* and log-6 for *Pseudomonas fluorescens* for the titanium surfaces.

[128] The second step is to minimize recesses on devices entering the lake or borehole. Recesses and intricate surface topography has been shown to promote microbial growth [*Ploux et al.*, 2009]. *Autoclaving* (sterilization using high-pressure superheated steam) is the only procedure that can reliably kill organisms in blind recesses, but it cannot be used for all materials, components, and subsystems. We have therefore limited the number and extent of recesses through design. Where a recess cannot be avoided, we use sterile liquids (for pressure communication and compensation) and elastomeric capping (potting) to provide a recess free and cleanable surface. All fluidic systems (e.g., the valve and pump system for the water sampler) are designed to enable flushing to enable cleaning with HPV and/or chemical wash (in our case, 70% ethanol).

[129] A third step is to limit handling of the equipment. The probe is designed to operate without being touched after final assembly, cleaning, and bagging. Targeted reliability design has been used to ensure that the sterile bagging is not opened to affect repairs or adjustments.

[130] The fourth step is to ensure containment. Once the engineered systems are assembled and cleaned, they must be protected against recontamination. All the systems are designed to be placed within protective environments, such as sterile bags, which protect them against unavoidable handling.

7.4. Microbial Control During Construction, Transport, and Deployment

[131] In the construction phase, a combination of post-manufacture cleaning and population reduction methods have been used to ensure the components are clean. The population reduction methods selected (from the short list below) depend on the material and design of the component. Assessment and verification have been undertaken at a process level in all cases and at a component level where required. The components have been assembled where necessary (e.g., where an inaccessible void is created such as in a gas-filled pressure case) in a clean room environment to ISO 14644 working to Class 100,000 (ISO 8) of this standard (the pharmaceutical industry sterilizes equipment in clean rooms as per ISO 14644). Terminal cleaning (i.e., at the end of the assembly) is used in all cases and may be sufficient for simple structures and subsystems. Subsequent to final terminal cleaning, equipment will be bagged and placed in a protective environment (e.g., heat sealed bagging or hard case).

[132] The sheaves, hot-water drill head, probe tether, and sediment corer mechanical systems will be sterilized using a combination of chemical wash, autoclaving, HPV, and UV postconstruction and assessed prior to being placed in a protective environment for transport to site. These items are manufactured from robust materials that can withstand harsh cleaning and population reduction methods (such as autoclaving). They are also simple in design and do not have enclosed recesses or voids, making them amenable to HPV treatment.

[133] The probe and sediment corer electronics modules must be cleaned and sterilized using HPV and, where materials are tolerant, by UV at a subsystem level. They will then be assembled in an ISO 14644 class 8 clean room, resterilized postconstruction, and assessed prior to being placed in a protective environment for transport. This preparation is required to ensure both protection of the environment and that scientific samples are not compromised with exogenous populations brought in on equipment. It is also required for these relatively complex systems where recesses and enclosed voids (e.g., seals and sealed pressure cases) cannot be avoided.

[134] The hot-water drill hose will be cleaned internally by HPV and cleaned externally through the production line bath prior to being capped for transport. The hose interior requires a greater sterility standard than the exterior and is too large to place in a protective environment. Before use, it will be jet washed with the drill water (at a minimum temperature of 90°C, filtered to 0.2 μm, and UV treated) and will then be continuously flushed with (the filtered and heated) water returning to the surface during pump operation. The cell count within the overlying snow at Lake Ellsworth

is 3.32×10^5 cells mL^{-1}. We expect the glacial ice to have a value no greater than this (probably lower), and the same holds for the lake also. Assuming we made no attempt to clean the borehole fluid, this would also be the upper value for the cell count within the borehole water. However, since we are UV radiating and filtering to >0.2 μm, we anticipate the borehole fluid to be far cleaner than the glacial ice it uses. In fact we estimate removal of all, if not the vast majority, of the bacterial cells by the cleaning process. We are therefore confident that the borehole fluid will contain fewer cells than the overlying ice sheet that melts into the lake.

[135] For transport, all equipment (including items in a protective environment) will be placed in 20 foot ISO shipping containers. The probe and sediment corer will be placed in containers, as will the probe sheave, winch, and tether. The containers will be closed with a combination of elastomeric compression seals and heat-sealed (ethylene vinyl acetate (EVA)) bagging. The integrity of the seal will be assessed using a positive pressure provided by filtered air and watching the pressure drop rate to assess leaks. The sealed containers will be shipped to site without breach of access and are designed to enable operation of the probe and corer without contact with the environment outside of the borehole. This is achieved by the use of flexible sterile links (tubes) and an air lock arrangement at the wellhead. Sterilization apparatus (HPV or UV; see below) will be included in the sealed winch container to mitigate the risk of seal breach.

[136] A mechanical drill will be used to create the top few meters of the borehole. The hole created will be further sterilized using a UV source lowered into the hole. The wellhead will be placed into this predrilled shallow borehole. UV exposure will be used to sterilize the drill hose sheave and wellhead exterior. The drill hose will be mounted onto a winch and passed over its sheave and uncapped prior to commencing drilling.

[137] The deployment procedure does not include assessment to provide data for control or verification of the processes once these are under way; that is, there will be no testing done in the field before use of the equipment. This would not be practical, because access of sealed engineering structures by field personnel would be a source of contamination, and analytical techniques with the required limits of detection take too long to provide meaningful feedback during the short duration (<24 h) of the experiment. However, where possible, samples will be taken for later analysis to assess the effectiveness of our procedures. For example, samples can be taken from the drill fluid and from surfaces of the retrieved probe without affecting our protection measures.

[138] Prior to the commencement of drilling operations, the wellhead UV collar (0.5 m diameter, 254 nm, 30 W) will be activated and the gate valves opened prior to lowering a UV source (254 nm, 30 W providing >10^4 reduction (requires >16 mJ cm^{-2} as per ANSI/NSF Standard 55–1991)) into the predrilled borehole. In the widest part of the borehole (0.5 m diameter), this source can pass at approximately 2 m s^{-1} and still meet the ANSI/NSF standard. This provides a sterile top section to the borehole. During drilling the exterior of the drill head and hose will be jet washed with drill fluid (which is filtered, heat sterilized (90°C), and UV treated) and will pass through the UV collar included in the wellhead. The function of the jet washing is to remove any remaining dirt and extraneous material from engineering surfaces. The efficacy of UV sterilization treatment increases with the energy density applied to the exposed surface. The hose moves slowly (0.5–1.0 m min^{-1}) enabling efficient coupling of UV energy onto its surface. A maximum UV dose of 2.2 J cm^{-2} is possible. The drill hose interior will be flushed with water generated from local melt (3 l s^{-1}, 90°C at the surface), filtered to remove particles >0.2 μm, and UV treated. The exterior of the hose will be flushed with a combination of this drill water and meltwater generated from the borehole drilling. This flushing enables significant dilution and removal of remaining microbes on the drill surface.

[139] On completion of the hot-water drilling the hose and drill head will be removed from the borehole. The hydrostatic level (i.e., the level of water in the borehole following breakthrough into the lake) is predicted to be approximately 284 m below the ice surface. The air-filled section of the borehole will be sterilized again using a UV source passed up and down this region. During this procedure the UV collar in the wellhead will be used to sterilize the tether for the UV source. On removal of the UV source the wellhead gate valves will be shut.

[140] The procedure for microbial control during deployment is identical for the probe and corer systems. Each is attached to a sealed container holding the tether and winch systems via flexible links (tubes) down which the tether can pass without coming into contact with the external environment (Figure 7).

7.5. Population Reduction Methods

[141] HPV will be used in the construction of many of the instruments and structures prior to shipping to Antarctica. HPV will also be used at the field site, but only in a planned way, to reduce exogenous microorganism populations where UV light penetration is not possible. It is the preferred method for planetary protection used by NASA [*Chung et al.*, 2008] and is widely used for decontamination of equipment and facilities including hospitals and large laboratories [*French et al.*, 2004; *Boyce et al.*, 2008; *Otter et al.*, 2009].

[142] Despite requiring a dedicated machine (to generate the vapor), heat and ventilation for a significant duration (~2 h in a room-sized space to enable the peroxide to degrade to harmless water and oxygen), this technique is attractive because systems are available commercially; it enables treatment of engineered structures with complex topography and small recesses; it can be used on a wide range of polymers and all electronic components [*Rogers et al.*, 2008]; it has high and proven efficacy (typically 10^6 reduction) [*Rogers et al.*, 2008]; and it does not result in a toxic end product requiring disposal [*Rogers et al.*, 2005]. HPV is effective against a wide range of organisms including

endospore-forming bacteria, biofilm-forming bacteria, and prions (proteinaceous infectious particles) [*Fichet et al.*, 2007].

[143] UV illumination will be used at the field site for treatment of the probe, the drill hose, and wellhead structures (including the air-filled section of the borehole). UV has the potential for high efficacy (>10^4 reduction), is portable, requires modest infrastructure, and is fast acting [*Wong et al.*, 1998]. However, efficacy is dependent on the energy coupled into the surface, which may be limited by surface shape [*Warriner et al.*, 2000a, 2000b]. It may be used (e.g., on the moving drill hose) in applications where other methods are impractical.

[144] Autoclaving is used in the construction and preparation of the probe (and the water sampler in particular). This method offers a proven and convenient method of treating resistant structures and is effective for closed volumes (e.g., water retained within a sample bottle). Autoclaving still remains the most popular method for sterilization of health care surgical equipment [*National Patient Safety Agency*, 2007] and glass and elastomeric components used in the pharmaceutical industry [*Agalloco et al.*, 2004]. This method is problematic for electronics and water-sensitive or temperature-intolerant materials that are used on the Lake Ellsworth probe preventing use on all systems. However, autoclaving is attractive for robust subsystems (e.g., the water sampler bottle).

[145] Chemical wash will be used in preparation of equipment where persistent microorganisms are encountered. We will not use this method extensively on site to reduce the complexity of environmental protection and site cleanup. Only 70% ethanol will be used in Antarctica (total 10 L) for laboratory sterilization and preparation of small items.

[146] HPV and UV treatment can be combined to increase efficacy up to 100-fold [*Bayliss and Waites*, 1979, 1980]. This technique will be used if sufficient standards are not achieved using other methods. The synergistic effects of UV and hydrogen peroxide lead to a generation of hydroxyl radicals that have lethal effects on vegetative bacteria and spores, [*Warriner et al.*, 2000a, 2000b]. This is because hydrogen peroxide is a photosensitizer that produces OH, peroxy, and hydroperoxy radicals [*Sosnin et al.*, 2004].

7.6. Verification and Assessment

[147] The efficacy of each of the microbial control methods described above is being verified in U.K. laboratory trials, backed up insofar as possible by in-field measurements. We have used positive control contamination by adherent bacteria, *Pseudomonas fluorescens*, to contaminate engineered surfaces and components. This species is commonly used as a model system and is representative of likely contamination of engineered structures. The level of contamination is being assessed, population reduction methods are being applied, and repeated measurement of population are being used to calculate the reduction achieved. This method allows accurate efficacy assessment, while minimizing error, by raising the number of cells well above the limit of detection.

[148] The analytical methods proposed are also being used for assessment of the standards achieved in the preparation of engineered systems. As stated above, the final assessment should generate a result at or below the detection limit of the analytical method and will be followed by a final population reduction step. This final step will not be assessed because the breach of protective environments required for assessment is a frequent cause of recontamination.

7.7. Nonrecovery of Equipment

[149] When drilling to the depths required to penetrate the lake, there is a risk of equipment loss. While the environmental consequences of such an occurrence would be minor, the program design has reduced its probability. The hot-water drilling method allows the hole to be rereamed allowing melting around potential stick points in a clean and efficient way. Such additional ice melting would release equipment effectively (i.e., in a matter of hours). Were any equipment to be lost in the lake, it could not be recovered easily. However, all mechanical connections meet standards developed in deep-sea exploration, which seldom experiences such loss of equipment. Importantly, one hose and one tether will be used, thereby avoiding the multiple connection issues that would otherwise be faced. Hence, the only weak points will be the connection between the hose and the nozzle and between the tether and the probe/corer.

8. CONCLUSIONS

[150] The proposed exploration of Lake Ellsworth will make profound discoveries regarding life in extreme environments and the history of the West Antarctic Ice Sheet. The latter is critical in assessing the present-day risk of ice sheet collapse and consequent sea level rise. The science is therefore of genuine interest to policy makers, the scientific community, the public, and the media. The program has been in a planning and design stage for 6 years, throughout which engineering challenges and environmental protection have been central and dominant features. Extensive information has been gathered on the baseline conditions, and robust mitigation measures have been incorporated to limit contamination. The proposed exploration program involves a main field season of 8 weeks during which time 10 staff will be on site to establish a drill camp (Appendix B) and run a hot-water drill for 3 days through 3.1 km ice to penetrate the subglacial lake. A probe and corer will then be deployed to allow water and sediment sample collection. A full assessment of potential environmental impacts has been undertaken. The most significant impact predicted is the potential for contamination of the lake and subsequent impact on microbial function. The lake's microbial populations are currently unknown and can only be determined through the exploration. This impact will be mitigated through the use of the hot-water drill methodology (using melted ice water heated to 90°C, filtered to 0.2 μm, and UV treated) and thorough microbial control contamination methods. We consider that the exploration of Lake Ellsworth will have a less than minor or transitory impact on the Antarctic environment. However, because of the uncertainties inherent in

such exploratory science, there is a risk of greater impacts (more than minor or transitory). As the actual impacts can only be assessed after they have already occurred, a precautionary approach has been taken reflecting this risk. This precautionary approach meets the recommendation of the NAS-EASAE report that "all projects aiming to penetrate into a lake should be required to undertake a Comprehensive Environmental Evaluation." We conclude that the global scientific importance and value to be gained by the exploration of Lake Ellsworth outweighs the impact the proposal has on the environment and justifies the activity proceeding. Results of the program will be known in 2013; this paper forms the necessary background on which they may be understood.

APPENDIX A: ALTERNATIVE APPROACHES

[151] Consideration of alternative methods, locations, timings, and logistical arrangements of the project is a fundamental part of the environmental impact assessment process, allowing environmental issues to be considered at the project design stage and assisting in the selection of the option with the least environmental impact. This section summarizes the alternative options considered by the Lake Ellsworth Consortium before the proposed methods were selected. Options relate to drilling method, microbial control, exploring alternative subglacial lakes, and not proceeding with the project.

[152] The Lake Ellsworth program has been in a development stage since 2004. During this time, the options available for lake access, direct measurement and sampling have been carefully considered. We are therefore extremely confident that there are no realistic alternatives to the scientific plan and goals discussed in this paper.

A1. Lake Access Technique

[153] Hot-water drilling was identified as the only means of obtaining rapid, clean access to Lake Ellsworth through 3 km of overlying ice, allowing the cleanliness criteria to be met, affording the maximum environmental protection without compromising the science aims.

[154] Mechanical drilling with the use of antifreeze fluids is inconsistent with the science and environmental aims of the project for two reasons. First, mechanical removal of ice requires both a substantial logistic effort and considerable time (at least two full seasons to drill to the ice sheet base). The consequence would be to drastically increase the cost of the program. Second, and most important, mechanical coring requires "antifreeze," which is commonly kerosene. Clearly such a substance, as the drill enters the lake, would pose a major contamination risk. Moreover, even if clean lake access was achieved, lowering a probe through the antifreeze-filled borehole into the lake would likely invalidate the scientific experiment (and offer further contamination risks).

[155] Access to the lake using a *thermoprobe*, a device that melts itself into the ice sheet unraveling a communications tether as it does so, is also not considered feasible for three reasons. First, in tests on glaciers, thermoprobes have proven very unreliable. The issue is that they melt out and accumulate non-ice particles in front of the probe that cannot be melted downward, and hence the probe direction is adversely affected. Second, the capacity to undertake science using a thermoprobe is restricted as a consequence of the large payload devoted to the unwinding tether. Third, the journey for a thermoprobe will likely be one-way, i.e., no return journey and no samples returned to the surface.

[156] This assessment, concerning the inappropriateness of ice cores and thermoprobes for subglacial lake access, is consistent with the NAS-EASAE report, which also concludes that holes developed through hot-water drilling "could be considered clean because the water used to melt the holes comes from the melted ice itself."

A2. Alternative Lakes

[157] Lake Ellsworth has been carefully considered as the most appropriate subglacial lake to meet the scientific aims of this project. *Siegert* [2002] undertook an assessment of all the subglacial lakes within the existing Antarctic inventory [*Siegert et al.*, 1996]. Using six criteria (Does the lake provide the greatest likelihood for attaining the scientific goals? Can the lake be characterized in a meaningful way (e.g., size, postulated structure)? Is the lake representative of other lakes and settings? Is the geological/glaciological setting understood? Is the lake accessible (close to infrastructure)? Is the program feasible within cost and logistical constraint?), Siegert concluded that a small lake at the ice sheet center, with access to appropriate nearby logistics, and with ice cover <3.5 km would be ideal as a candidate for lake exploration. In 2004 Lake Ellsworth was the only known candidate in West Antarctica that met these criteria (and still is). Other lakes in West Antarctica are likely to be either logistically challenging to gain access to, are located away from the ice divide, or, in the case of Siple Coast lakes (the target of the U.S. Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) program), are far younger than Lake Ellsworth, and are therefore unlikely to be a habitat in which life, and an ecosystem, has developed over long periods of time. Furthermore, only very old lakes at the center of the ice sheet are likely to persistently accumulate sedimentary material necessary for the development of a record of glacial and climate history. For these reasons, *Siegert et al.* [2004] proposed Lake Ellsworth as the best candidate for exploration in West Antarctica. As a consequence, the geophysical exploration of Lake Ellsworth was undertaken in 2007–2008 and 2008–2009. The result is a full appreciation of the ice cover, ice flow, water depth, water flow, and lake floor substrate of Lake Ellsworth. No other lake has such information regarding its physiography, which makes Lake Ellsworth unique in its appropriateness for direct measurement and sampling. The scientific questions regarding West Antarctic Ice Sheet history cannot be answered, obviously, in East Antarctica, thus ruling out such lakes for this particular program.

A3. Microbial Control

[158] The most significant environmental impact results from the potential to affect the lake's natural microflora, and a great deal of consideration has gone into the selection of microbial control methods. Alternative methods considered but ruled out are discussed below.

[159] The first alternative is chemical-wash methods. Many of the chemical washes lead to degradation of the materials being cleaned and hence are not suitable for this program [*Barbut et al.*, 2009].

[160] The second alternative involves plasma treatment of surfaces, using highly energized gases. *Low-temperature plasma treatment* (LTPT) is suitable for heat-sensitive materials, such as electronic components. LTPT exposes any microorganisms present in the sample to an electrical discharge with biocidal effects [*Moisan et al.*, 2001]. Low pressure plasma treatment (LPPT) is used for surgical instruments and usually includes a UV irradiation step for genetic material destruction [*Kylián and Rossi*, 2009]. Chlorine dioxide vapor (CDV) is suitable for heat-sensitive materials and therefore could be used for electronic components in the probe, for example. Large-scale applications of this method are currently developed for the decontamination of whole buildings from *Bacillus anthracis* [*Wood and Blair-Martin*, 2009]. While effective, these methods are less suited to the Lake Ellsworth program because of disposal, the infrastructure required, or flexibility.

A4. Not Proceeding

[161] Not proceeding with this project, i.e., the "do nothing" option, would avoid realizing the associated environmental impacts. It would, however, mean that the benefit to global science and policy would also not be achieved. Understanding the glacial history of the WAIS is critical to assessing the present-day risk of ice sheet collapse and consequent sea level rise. It is proposed that new and valuable information on past ice sheet behavior may be present in the sediment cores in subglacial lakes such as Lake Ellsworth. This information is urgently required to inform policy makers on their response to sea level change and climate change impacts. Identification of life within subglacial lakes would be a major scientific discovery. SCAR has been supporting scientific planning to achieve this type of exploration since 1999. Planning over the subsequent 10 years has been necessarily slow yet purposeful. As a consequence of this planning, the scientific community is now ready to undertake the direct measurement and sampling of subglacial lake environments.

APPENDIX B: DESCRIPTION OF THE CAMP AND THE LOGISTICS

[162] The camp will be established during the 2012–2013 Antarctic season for a period of approximately 8 weeks and will take the form of a static field operation camp. The site is separated into three main areas: the drilling site (working area), the camp site (living area), and the generator area. The drilling site will consist of all the equipment for undertaking the drilling and sampling operation, the camp site will consist of the sleeping and messing accommodation as well as some basic lab and office space, and the generator area will contain the four generators required to run both the drilling site and the camp site. The layout of the site is a balance between what is desirable and what is practical. Some of the key considerations that shaped the initial site layout were as follows:

[163] 1. Minimum distances between objects/areas, to allow safe working access, to minimize drifting snow, to allow correct feed angles between winches and sheaves, to minimize noise pollution in the sleeping accommodation.

[164] 2. Maximum distances between objects/areas, dictated by current carrying capabilities of cables, heat loss from hoses, travel distances between areas.

[165] 3. Site orientation, so that the prevailing wind minimizes the emissions near the wellhead and instruments from the generators, the boiler, and the vehicle (deployment crane).

[166] 4. Logical flow to the water, electricity and fuel lines, making the setup and maintenance of the site more intuitive and safe.

[167] The current site layout (Figure A1) provides a good working balance of these factors which can be refined as the design of the equipment progresses. The three main areas will be separated by approximately 50 m. Living and working environments will be a combination of tents used by the BAS as standard items at other field sites. The majority of the drilling and sampling equipment will be housed in lightweight ISO 20 foot shipping containers, making transport and deployment relatively straightforward. Power will be provided by four standard generator sets running on AVTUR fuel (Jet A-1). They will provide 240 V, 50 Hz, 1 Ø power to the domestic camp and 415 V, 50 Hz, 3 Ø power to the drilling site. Fuel will be transported and used in two ways: (1) Drummed fuel will be used to supply the generator sets and vehicle, and (2) bulk fuel (using flexible bladders) will be used to supply the hot-water boiler. There will be a communications link between the domestic camp and the drilling site allowing remote observation and operation of equipment. The on-site team for the 2012–2013 drilling season will be composed of 10 people, covering the following roles: program manager, responsible for overseeing the operation; two drilling engineers, responsible for the drilling the hole; two instrument engineers, responsible for deploying the instrumentation; plant engineer, responsible for power generation, vehicles, and fuel management; three scientists, responsible for directing and handling the samples; and camp manager, responsible for running the domestic camp and waste management.

[168] The fuel required on site for drilling, power generation, and other logistics will amount to approximately 51,250 L of AVTUR (enough to drill two 3100 m boreholes, thus allowing contingency within the drilling operation) and 1025 L of unleaded petroleum spirit for generators, power tools, etc. This will fuel all equipment and vehicles directly associated with the program, including the refueling of the BAS DeHavilland Twin Otter aircraft. This does not include fuel for the tractor

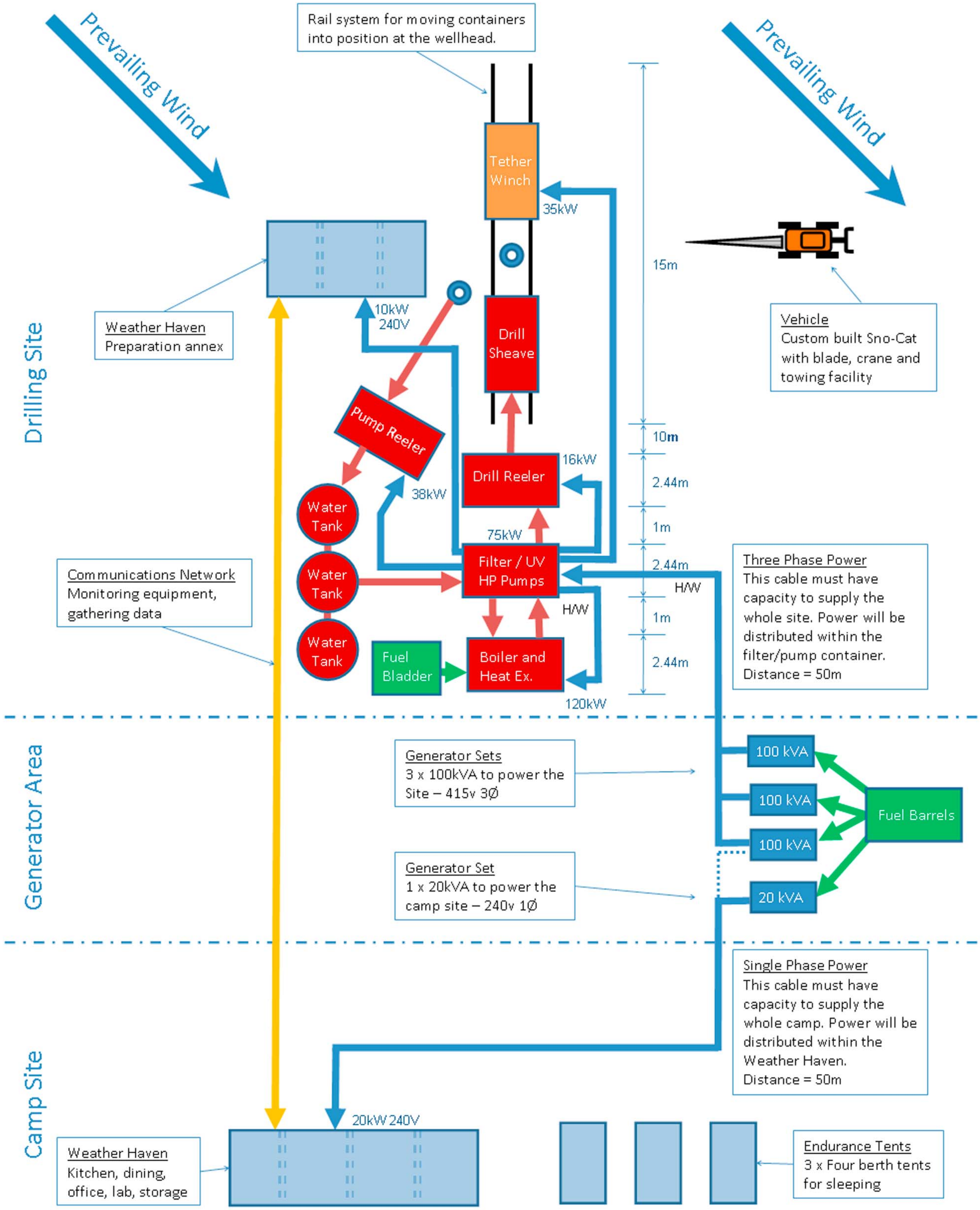

Figure A1. Schematic layout of the camp.

train or the intercontinental Ilyushin IL-76 flights provided by Antarctic Logistics & Expeditions LLC (subsequently referred to as ALE). Fuel is to be transported to site by ALE using sledges in a combination of 205 L drums and bulk fuel flexible bladders (5800 L or 1500 U.S. gal. each bladder). Four of these bladders will be required to provide a sufficient, uninterrupted fuel supply for the hot-water boiler.

[169] The only vehicle used on site will be a Tucker Sno-Cat (or similar) modified by attaching a hydraulic crane. It will provide a towing facility, a snow-clearing blade, and a 7.2 m reach hydraulic crane. The vehicle will be modified to run on AVTUR fuel, reducing the number of different fuels required on site. The vehicle will be fully serviced and optimized prior to deployment, and a "scrubber" will be fitted to the breather and exhaust to further reduce emissions. The vehicle will be maintained on site by an experienced plant technician.

[170] Water for the domestic camp and the drilling operation will be produced from melted snow. It is anticipated that the drilling operation will use a maximum of 90,000 L and the domestic camp will use a maximum of 10,000 L of water. The wastes generated throughout the duration of the program will include human wastes (sewage), food wastes, food packaging, gray water, fuel drums, and batteries. There will also be a small amount of waste oil (~15 L) from the 30 kVA generator which will require a service midseason. All waste materials will be stored on site in appropriate containers pending removal at the end of the field season for appropriate disposal outside Antarctica.

[171] There will be a comprehensive communications infrastructure on site consisting of an Iridium satellite system providing voice and data capability, high-frequency (HF) radio providing long-range voice capability, and very high frequency (VHF) handheld radios providing local communications around the site. There will also be a local area network providing a method of storing and accessing data and e-mail, as well as providing a method of remote monitoring of the drilling equipment and generator plant.

[172] The science equipment (including the hot-water drill, winch, drilling hose, etc.) and the auxiliary equipment (such as the generators, vehicle, domestic camp, etc.) will have a total combined weight of ~60 t, and the fuel supplies will weight a further ~55 t. The majority of this equipment will be shipped to Punta Arenas, Chile, on the RRS *James Clark Ross*. From there, it will be moved to the ALE base camp by Ilyushin IL 76 heavy lift aircraft. Five rotations of aircraft will be required to transport the equipment into Antarctica over a period of two Antarctic seasons. Onward transport will then be via a tractor train to the Lake Ellsworth site, via the Ellsworth Mountains, using up to two tractor and sledge units, each towing circa 18 t of cargo. Between 10 and 12 tractor traverses will be required to transport equipment and fuel to the drill site. The tractor route from the ALE base camp to Lake Ellsworth is 295 km long. Reconnaissance work carried out during the 2010–2011 season by ALE confirmed this is crevasse-free and workable. Personnel, some field support, and light science equipment will be transported by BAS Twin Otter aircraft from Rothera over a number of flights through the program duration.

[173] At the end of the 2012–2013 field season, the camp and equipment will be derigged and packaged for transport. All science samples and personnel will be transported off site at this time, along with some waste. This will be done using a combination of BAS Twin Otter through Rothera and ALE tractor train through the Union Glacier base camp.

[174] The camp, the remaining waste, and some field equipment will be moved off site during the 2013–2014 season by ALE. No equipment will be left at the Lake Ellsworth drilling site. The area will be groomed after the removal of all the equipment so that the site is returned, as far as possible, to its original condition. The hot-water drilling system will be transported by ALE to another location, as it is due to be used by another science program during the 2014–2015 season.

[175] The program team recognizes the need for support from an established forward camp in the event of operational or serious health and safety incident. Such support will be provided by ALE from their base camp, and by BAS from Rothera, both of which have a 24 h emergency communication and listening service. The BAS Twin Otter aircraft will provide search and rescue capability.

[176] All work on site will be governed by a comprehensive set of safe working procedures backed up by many months of training prior to the commencement of the field season. All risks will be identified, and safe procedures will mitigate these as far as possible. The program manager on site will be responsible for ensuring that these procedures are followed at all times.

[177] Where the consequence of a risk is unknown but facing it is unavoidable, e.g., the risk of a clathrate reaction while drilling at the point of breaking through to the lake, the safe site procedures will ensure that all personnel are clear of a predefined exclusion zone and that the equipment can be operated remotely from outside of this zone.

GLOSSARY

Adenosine triphosphate (ATP): A biomolecule found in all living cells. Its function is the transport of energy around the cell, and it can therefore be an indicator of whether a cell is living or dead. Chemically, it is a nucleotide.

ANDRILL: Antarctic Drilling Project. A scientific sediment drilling project in Antarctica gathering information about glacial history and past periods of global warming and cooling.

Autoclaving: An instrument sterilization technique that uses high-pressure superheated (120°C) steam, usually for >10 min.

Bathymetry: The study of the underwater depth of lakes or ocean floors.

Bed-reflection power (BRP): A calculation of the power of a radio wave reflection at a surface.

Bentley Subglacial Trench: A vast ice-covered topographic feature in Marie Byrd Land, West Antarctica. At 2555 m below sea level, it is the lowest point on the Earth's surface not covered by an ocean.

Bridging stresses: Many subglacial lakes are located in troughs that have a width similar to, or less than, the ice thickness. In such cases, the ice may effectively act like a beam between two higher ground points, making it difficult to ascertain, from consideration on ice surface and ice-water interface slopes, whether the lake is floating.

Byrd ice core: A 2164 m long ice core recovered from Byrd Station in central West Antarctica in 1968.

Clathrate: A chemical substance consisting of a lattice of one type of molecule trapping and containing a second type of molecule. A clathrate hydrate, as hypothesized to exist within some subglacial lakes, involves a lattice of water molecules trapping molecules of gas.

COMNAP: The Council of Managers of National Antarctic Programs.

Coriolis effect: An apparent deflection of moving objects when they are viewed from a rotating reference frame, such as the rotation of the planet. In the Southern Hemisphere, this deflection is to the left.

Diatoms: One of the most common types of phytoplankton, which live in the near surface of the world's oceans and seas.

Digital elevation model (DEM): A depiction of a surface characterized as the elevations of cells within a grid. DEMs can be constructed from irregularly spaced data (such as RES surveys) using interpolation procedures to calculate elevations between known data points.

Dissolved gases: Gases held in solution. Liquids, such as water, have a dissolved gas threshold, which is the maximum level of gas that can be dissolved at a given temperature and pressure.

Dissolved oxygen (DO): One of the measurements taken by the lake probe.

EDML: The EPICA (European Ice Coring in Antarctica project) at Dronning Maud Land, in East Antarctica.

Electrical conductivity (EC): One of the measurements taken by the lake probe.

Eolian dust: Windblown dust material.

Europa: The sixth moon of the planet Jupiter and the smallest (1/4 of Earth's radius) of the four moons discovered (in 1610) by Galileo. It is thought to have an ice crust overlying a body of water above silicate rock and an iron core.

Fluorescent in situ hybridization (FISH): A technique used to detect and localize the presence or absence of specific DNA sequences on chromosomes.

Frazil ice: Loose, randomly oriented needle-shaped ice crystals in water that appear as a "slush" and make the first stage in the formation of sea ice and, as has been hypothesized, the accretion of ice above a subglacial lake.

Gas chromatography–mass spectrometry (GC-MS): A method that combines the features of gas-liquid chromatography and mass spectrometry to identify different substances within a test sample.

Geomorphology: The study of Earth surface landforms and the processes responsible for their formation (often referred to as morphology).

Geothermal heating: Heat experienced at the Earth's surface derived from its interior due to radioactive decay within the mantle.

GPS: Global Positioning System, commonly used in glaciology to determine the location of seismic and RES data. It can also be used to measure the accurate (<1 m) location of fixed poles that, if resurveyed several months to a year later, can reveal the surface velocity of ice flow.

High-performance liquid chromatography (HPLC): A chromatographic technique to separate a mixture of compounds.

Hot-water drill: A technique used commonly in glaciology to access the subsurface of an ice mass. The technique is very simple. A pool of glacier ice is melted and then heated and pumped into a high-pressure hose. The hose is pointed downward into the ice, and the hot water that comes out melts a hole. The new melted water, plus the water that comes out of the hose, is pumped back to the surface and reheated and pumped down again. The width of the hole created can be adjusted by the rate of lowering of the drill hose.

Hydrogen peroxide vapor (HPV): A gaseous form of hydrogen peroxide, used as a sterilization technique.

Hydrologically closed: Referring to a subglacial lake that is unable to issue water downstream.

Hydrologically open: Referring to a subglacial lake that can both accept and issue subglacial water.

Hydrological potential: In hydrological terms, the potential energy held by a water body.

Ice cores: Samples of ice recovered from ice masses. In Antarctica and Greenland, ice cores can be several kilometers long and contain, within the ice, climate records dating back several glacial cycles (e.g., >700,000 years for the case of the Dome C EPICA core; >400,000 for the case of the Vostok ice core). Ice cores are recovered using a mechanical drill, needing antifreeze to lubricate the drill bit as it penetrates into deep, cold ice.

IceCube: A U.S. program to detect neutrinos (similar to electrons but with no charge and able to pass through matter largely unaffected) at the South Pole, using deep (>1 km) boreholes to install sensors.

Ice-water interface: The boundary at the surface of a subglacial lake, thought to be a location in which microbial communities may concentrate.

Infrared Raman: A spectroscopic technique (to examine the relationship between matter and emitted energy) used to study vibrational, rotational, and other low-frequency modes. It relies on inelastic scattering, or Raman scattering, of monochromatic light from the infrared range.

ISO: International Organization for Standardization.

Lake Concordia: A relatively large (~60 km long) subglacial lake in the Dome C (lake district) region of East Antarctica.

Limnology: The scientific study of lakes and material within them.

Line of maximum density (LOMD): On the Earth's surface, water becomes less dense as it cools below ~4°C. In high-pressure regions, such as at the bottom of deep oceans, this relationship is reversed, meaning that cool water sinks to the floor rather than rises (as in the case of surface lakes). The line of maximum density marks the separation within a deep-water body of these two zones.

Low-temperature plasma treatment (LTPT): A method used to kill microorganisms in a wide range of applications (including medical). Electric fields are used to produce a plasma in a known gas. At low temperature this creates a mixture of ions, electrons, radicals, atoms, and molecules that interact with organisms that are exposed to it. The lethal mechanisms include UV light emission from the plasma and interactions of reactive or energetic species with cell membranes and contents.

Molecular biology: The branch of biology dealing with the molecular basis for life.

NGRIP: North Greenland Ice Core Project.

Oligotrophic: An environment offering little by way of chemicals and energy to sustain life.

Phylogenies: The evolutionary links between groups of organisms.

Physiologies: The mechanical, physical, and biochemical study of organisms.

Polythermal-based glaciers: Ice bodies that contain frozen and melting zones at their bases. Normally in glaciology, polythermal glaciers exhibit surface runoff that permeates to the bed in some places.

Probe: A device with sensors and samplers to enable in situ investigation of remote environments.

Quantitative PCR (qPCR) enumeration: A method for enumerating the number of original DNA sequences in a sample, using the polymerase chain reaction. Combined with fluorescence technology, it can give an accurate indication of a microbial population size.

RABID: A U.K.-led project to measure the basal conditions of the Rutford Ice Stream in West Antarctica.

Radio echo sounding (RES): Technique developed in the 1960s to sound the base of polar ice sheets. RES uses VHF radio waves emitted from the ice surface, which reflect off surfaces with a dielectric contrast (such as the base of the ice sheet). In the late 1960s, RES was deployed on aircraft to begin the survey of Antarctica's sub-ice geomorphology. RES is a particularly good technique to identify subglacial lakes, as there is a significant difference between the dielectric contrast of an ice-water interface compared with an ice-rock or ice-sediment interface. Radio waves are absorbed in water, however, which means the technique cannot be used to determine the thickness of subglacial water bodies in excess of a few meters thick.

Scientific Committee on Antarctic Research (SCAR): A committee of the International Council of Science (ICSU) that exists to initiate, promote, and coordinate scientific research in Antarctica. SCAR also provides international, independent scientific advice to the Antarctic Treaty system and other bodies.

Sediment corer: A device capable of extracting an undisturbed, cylindrical sample of sediment. Most sediment corers will acquire a core of a few centimeters in diameter and several meters in length.

Seismic surveys: The use of controlled sound waves (e.g., small explosions) to determine the position and orientation of subsurface features. In reflection seismics, the sound waves reflect off surfaces of differing densities. If the sound velocity of the medium in which the waves propagate is known, this technique can be used measure the depth of reflections. For large ice sheets this means the ice sheet base and, as sounds waves travel well in water, the base of a subglacial lake.

Snowball Earth hypothesis: The hypothesis that some time before 650 million years ago, the entire Earth surface was covered (at least once) by ice.

STP: Standard temperature and pressure.

Subglacial lakes: Bodies of fresh water beneath permanent ice cover. In Antarctica, over 350 lakes have been identified beneath ice >2 km thick.

Thermoprobe: A notional device to provide clean access to the subsurface of ice sheets. The probe is tethered to the ice surface, which supplies power to the front end of the probe. This power is used to melt ice, and, under gravity, the probe descends the ice column. There are three problems with the use of thermoprobes in glaciers. First, their path downward is affected by the accumulation of dust at the melting end of the probe, forcing it to veer from the vertical. Second, the power tether unwinds from within the probe itself, meaning that deep beneath a large ice mass much of the probe will be empty. Third, it is unlikely that a thermoprobe can be recovered.

Transantarctic Mountains: A range of mountains that extends across the continent from northern Victoria Land to Coats Land, serving as the division between East Antarctica and West Antarctica.

U-shaped trough: A classic glacially carved macrogeomorphological valley (U-shaped in cross section), seen commonly in alpine settings and formerly glaciated uplands.

U.S. National Academy of Sciences: An organization whose members serve to advise the nation on matters relating to science, engineering, and medicine. Members of the organization are elected annually by current members based on their research merit.

Vostok Subglacial Lake: The largest and best known Antarctic subglacial lake, known commonly as Lake Vostok. The lake, located beneath 3.7–4.2 km of ice, is >250 km long and as great as 80 km wide. The Vostok ice core exists over the southernmost end of the lake, where the ice is thinnest (at 3741 m).

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